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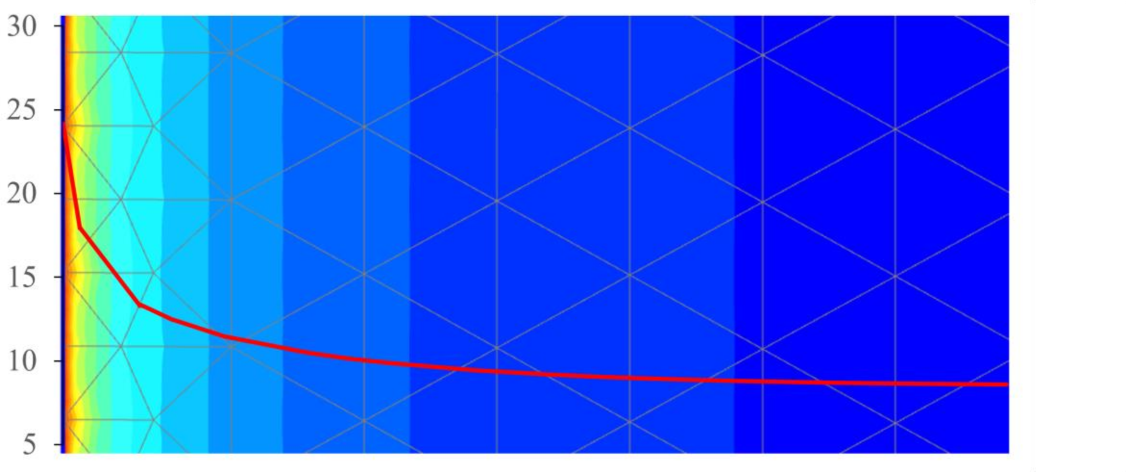

A numerical study on the thermo-mechanical behaviour of Gothenburg clay

Master's thesis in Infrastructure and Environmental Engineering

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Master’s thesis ACEX30

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Master's Thesis ACEX30-

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Cover: Calculated temperature distribution around a thermal pile during heating.

Abstract

The study of thermal piles is one of the new and complex research areas in geotechnical engineering, where the coupled thermo-mechanical behaviour in the soil surrounding the pile needs to be understood, whether in the heating or cooling stage. This thesis focuses on studying a metal pile which is subjected to thermal loading of heating for 21 days and 13 days of cooling. Several variables were investigated during the research, such as the effect of changing the soil thermal properties (i.e., heat capacity, thermal conductivity), and changing the soil mechanical model (i.e., linear elastic, Modified Cam Clay).

In addition to the temperature distribution in the soil, the developed excess pore water pressure was also investigated for several values of the volumetric thermal expansion coefficient. These results were compared with the experimental study of an in-situ pile filed in the Utby in Gothenburg (Bergström, 2017).

The study shows, on one hand, that the thermal flow calculations yielded a good agreement between the numerical and experimental values where the heat spreads to about 2 m from the pile, then returns to the earth natural temperature of 8.5^{o}C. On the other hand, changing the thermal properties and changing the used soil constitutive model has minor effects on the results. Additionally, the pile mechanical loading did not affect the heat spread if compared to the case of loading free. As for the excess pore water pressure, the selected models for the numerical study could not capture the experimental measurements suggesting that a more advanced soil model is needed to replicate the thermal effects on the excess pore water pressure.

Keywords: PLAXIS 2D, Thermal effects, Heat capacity,
Thermal conductivity, linear elastic, Modified cam clay.

Acknowledgements

I want to express my sincere gratitude to my supervisor Ayman Abed, Senior Lecturer at Chalmers and my examiner Jelke Dijkstra, Professor at Chalmers for their encouragement and contribution with expertise throughout the work. With their support, motivation, and inspiration, I developed my knowledge in the field.

Lastly, I would like to express my gratitude to my family and friends who have been by my side during the process.

Iyas Alasfar, Gothenburg, June 2022

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Nomenclature

Abbreviations

LE	Linear Elastic
MCC	Modified cam clay

Greek letters

γ_{sat}	Wet unit weight
$\gamma_{\mathrm{uns.sat}}$	Dry unit weight
κ^*	Modified swelling index
λ^*	Modified compression index
ν'	Effective Poisson's ratio
ν_{ur}	Poisson's ratio for unloading and reloading
ϕ	Friction angle
ϕ_c'	Friction angle at critical state
ψ	Dilatancy angle
σ_c'	Pre consolidation pressure
ε_{vx}	Volumetric strain in x-direction

Roman upper-case letters

E'	Effective Young's modulus
G	Shear modulus
K_0	Earth pressure coefficient at rest
K_0^{NC}	Earth pressure coefficient for normally consolidated soils
K_{0z}	Lateral earth pressure coefficient
L	Length of the pile
M_0	Constant constrained modulus below effective pre-consolidation pressure
R	Radius of pile
R_{intar}	Interface factor
X_{min}	Left horizontal boundary
Y_{min}	Bottom vertical boundary

Roman lower-case letters

k_x	Permeability in horizontal direction
k_y	Permeability in vertical direction
K'	Cohesion intercept
c_u	Undrained shear strength

1 Introduction

1.1 Background:

Several studies have been performed on the thermal pile systems in the past years to study their thermal behaviour. Some of these studies are experimental, and others are numerical. Thermal piles were initially developed in the early seventies (Bergström, 2017) which are structural piles with other tubes to circulate heat transfer fluid. These systems have been distributed widely in Europe and other parts of the world in recent years because of their many positive advantages. Thermal piles help in storing and recovering energy from the ground. This type of pile is used as a source of renewable energy in modern cities (Wuttke et al., 2016). It has significant environmental benefits by reducing carbon dioxide emissions (Nguyen, 2019.). This is in addition to its economic benefits due to reduced installation costs in comparison to conventional geothermal probes (Wuttke et al., 2016). The clay is one of the most common soils in Sweden (Bergström, 2017). Therefore, piles are often used as foundations in buildings. This system of heat exchanger tubes is included within a group of pipes, allowing the exchange of heat energy between the ground and the building through a fluid that passes through these piles (V. T. Nguyen et al., 2017).

On the other hand, soft soils, such as clay, are likely to be affected by the additional thermal cycles generated by the thermal pile. Several studies have been accomplished in recent years to investigate the thermo-mechanical behaviour of energy piles. The results indicate to the effect of temperature change on the interaction between soil and resistive piles.

1.2 Aim and objectives:

- The main goal of this study is to investigate the effect of temperature variation imposed by thermal piles on the mechanical behaviour of the surrounding soft clay.
- To achieve a better understanding of the effect of temperature, the results of coupled thermo-mechanical finite element modelling will be compared to available experimental data of field thermal pile tests.
- Sensitivity analysis will be carried out on the thermal and mechanical properties of soil to investigate how they would affect the soil response.

1.3 Limitations:

- The thermal pile can have different functions, but the focus will be only on the effect of the thermal loading on the geotechnical response of the soil.
- The study will focus on the numerical simulation of the in-situ experiment in Utby, in particular the thermal response test. The study will not deal with a pile group's behaviour but will focus on a single prefabricated steel pile.

2 Literature review

2.1 Heat Transfer in Soils:

Heat travels through material media in three ways: conduction, convection, and radiation. The transition is from the medium with higher temperature to the medium with lower temperature. Heat is transferred through them through transport and convection because the soils of their structure that simultaneously contains solids, gases, and liquids. Transfer occurs in the solid part of the soil and to a lesser extent in the fluids in the soil voids (water or air) due to heat transfer through the particles of the material. The transfer occurs via fluids due to the different densities of the liquid due to changing temperatures, which leads to convective currents within the fluid(Evgin, 2017).

In general, determining the method of heat transfer in soils is a complex matter linked to many factors such as the soil's grain gradient, the degree of saturation of the soil, and other factors. It allows heat transfer by more than one mechanism (transfer and convection together) (Sedano & Evgin, 2017).

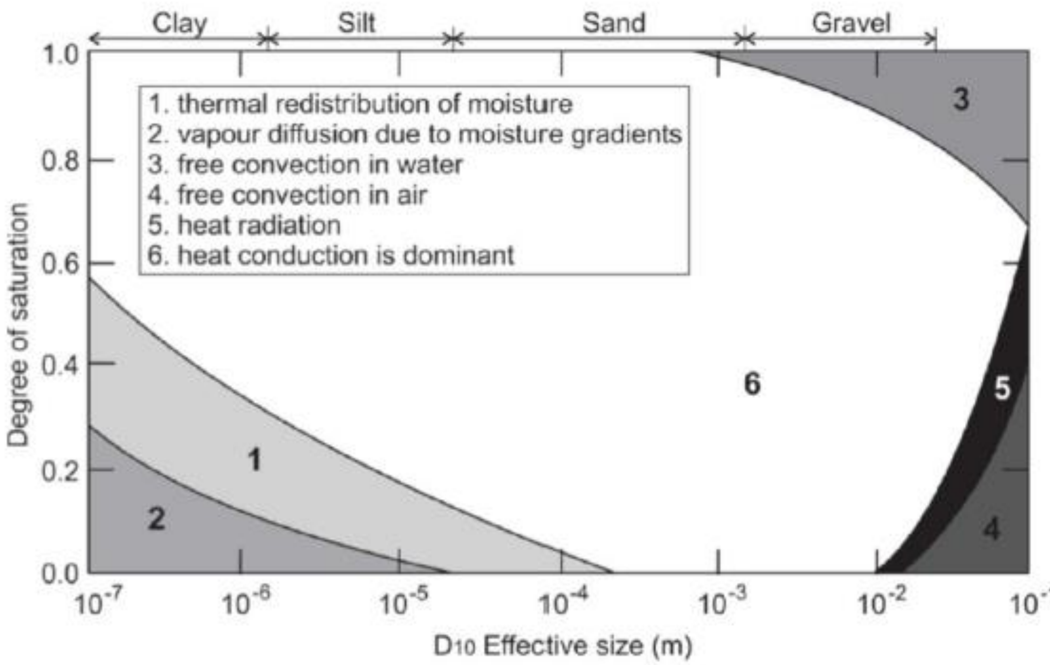


Figure 2-1 Heat transfer mechanism through the soil depending on the degree of saturation and the dimensions of the soil . (Sedano & Evgin, 2017)

2.2 Thermal properties of the soil:

In general, soils have several thermal properties, including:

2.2.1 Thermal conductivity of soil (Kt):

It is defined as the amount of heat transferred through a section of soil area A = 1 m2 during one time when a temperature difference of ΔT = 1 K is applied, and it is estimated by (J/m.s.K), and the following relationship expresses it:

$$Kt = \frac{q}{A.(T1 - T2).L} \tag{2.1}$$

Q is the amount of heat passing through the surface of an area. An L is the length of the soil element.

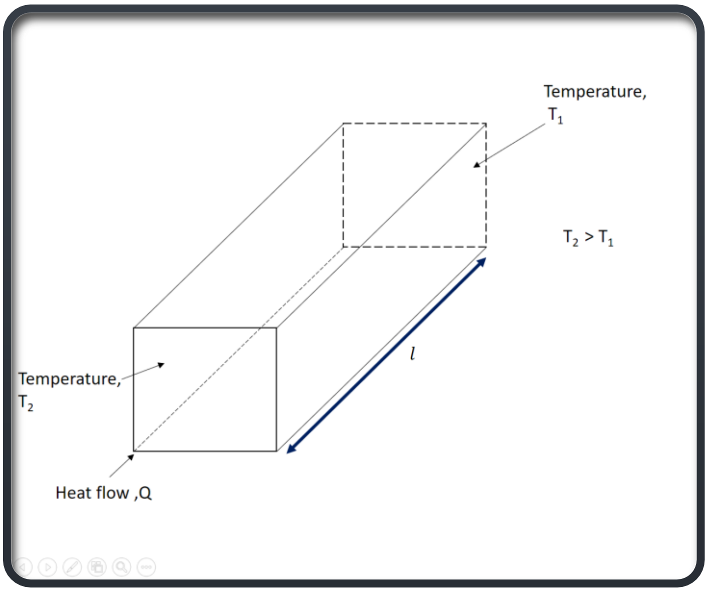


Figure 2-2 A soil element exposed to thermal flow.

The solid part of the soil determines this property. Usually, the conductivity of water and air present in the soil voids is low compared to the conductivity of the solid grains of soil (in contrast to ice, whose conductivity is four times greater than the conductivity of water). It expresses the flow of heat through the ground; the more significant the conductivity, the soil can transfer heat faster.

2.2.2 Heat capacity (C):

$$C = \frac{q}{m} \quad (2,2)$$

It is defined as the amount of heat needed to raise the temperature of a mass of soil volume 1 m^3 by one degree Celsius(Omar T, 1981):

Where m is the soil mass

2.2.3 Diffusion (α):

It is the ratio of conductivity over the heat capacity of the soil, and it is estimated at (m^2 / s) and is given by the following relationship:

$$\alpha = \frac{Kt}{C.\rho} \quad (2,3)$$

Table 2-1 Table showing conductivity, heat capacity, and diffusivity values for different soils (Wiley & Sons, 2013).

Material	Density $\rho(kg/m^3)$	Specific Heat c(J/kg.°C)	Thermal Conductivity k(J/s.m.°C)	Thermal Diffusivity $\alpha(mm^2/s)$
Air	1 to 1.4	1000 to 1050	0.02 to 0.03	13 to 30
Water	960 to 1000	4190 to 4220	0.5 to 0.8	0.13 to 0.17
Ice	917 to 920	1960 to 2110	2.0 to 2.6	1.24 to 1.52
Clay (unfrozen)	1400 to 1800	750 to 920	0.8 to 2.8	0.1 to 1.66
Clay (frozen)	1400 to 1800	650 to 800	1.0 to 3.6	0.15 to 2.3
Sand (unfrozen)	1500 to 2200	630 to 1460	2.3 to 3.8	0.87 to 3.0
Sand (frozen)	1500 to 2200	500 to 1200	2.9 to 4.7	1.2 to 4.2
Rock	2200 to 3000	710 to 920	2 to 6	1.1 to 3.0

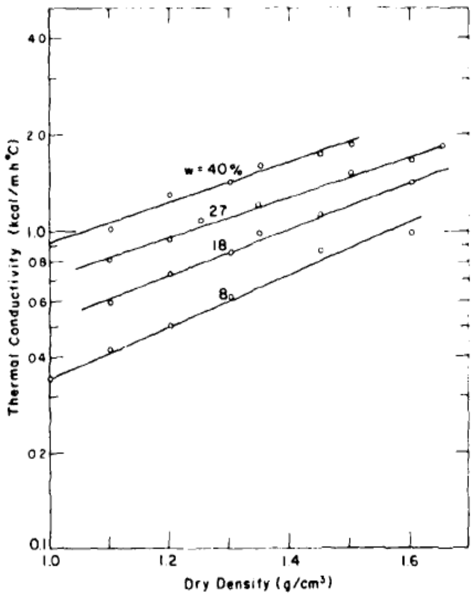


Figure 2-3 Change in the thermal conductivity of non-frozen clay soils by changing their dry density and moisture (Faroukl, 1981).

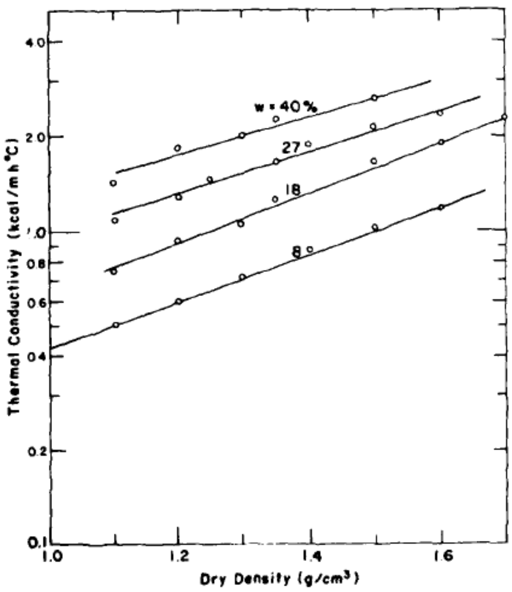


Figure 2-4 Change in the thermal conductivity of frozen clay soils by changing their dry density and moisture (Faroukl, 1981).

Another factor of soil properties significantly impacts the thermal conductivity of soils regardless of the type of soil, which is the volumetric water content θ. In general, increasing the water content of soils will increase the tin thermal conductivity of soils, partly due to high thermal conductivity of water. (Kaveh et al., 2021).

The following relationship between thermal conductivity and volumetric water content (Kaveh et al., 2021) :

$$Kt = A + B\theta - (A - D)e^{-(c\theta)^E} \quad (2,4)$$

Factors A, B, C, and E are empirical factors determined according to soil type and chemical composition.

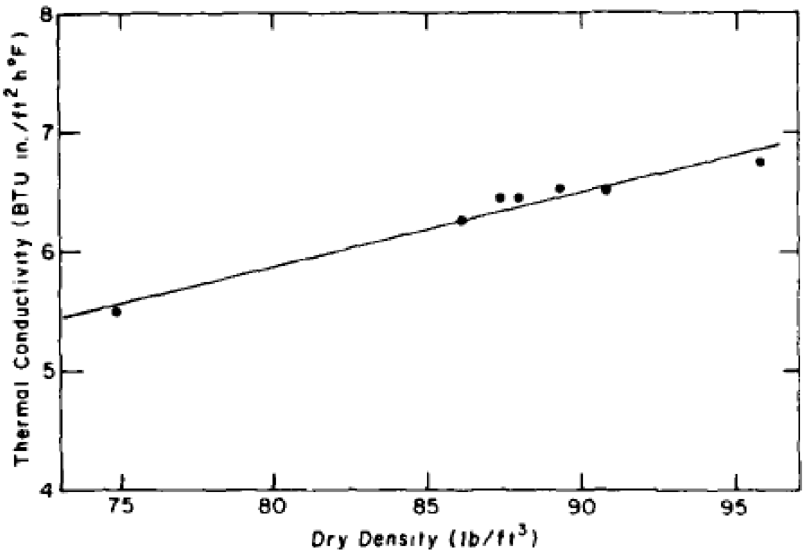


Figure 2-5 The change in the thermal conductivity of saturated clay soils in terms of their dry density (Faroukl, 1981).

Christine 1945 suggested the following relationship for calculating the thermal conductivity of soils at the ideal moisture in terms of the dry density of the soil:

$$Kt = A.(10)^{B.\gamma d} \quad (2,5)$$

γ_d dry density of Soil Kg/m^3

Factors (A, B) values vary according to the soil type like (sand or clay) and whether the soil is frozen.

Johnson 1975, suggested the following relationship in the case of natural dry soils (Loveridge et al., 2013):

$$Kt = \frac{0.135\gamma d + 64.7}{2700 - 0.974\gamma d} \quad (2,6)$$

As for the dry crushed rocks, he suggests the following relationship in terms of its porosity n:](Faroukl, 1981)

$$Kt = 0.039\, n^{-2.2} \qquad (2,7)$$

(n) soil porosity

As for unsaturated soils, the following relationship was suggested by researcher Johnson: (Leugim Corteze et al., 2019)

$$\mathrm{Kt} = (Ksat - Kdry)\lambda + Kdry \qquad (2,8)$$

$$\lambda = 0.7.log(Sr) + 1 \qquad Sr > 0.5 \qquad (2,8,1)$$

$$\lambda \; = log(Sr) + 1 \qquad Sr > 0.1 \qquad (2.8.2)$$

Whereas K_{dry} conductivity of dry soil $\mathbf{K_{sat}}$ conductivity of saturated soil Sr is the degree of saturation of the soil.

It was found that the thermal conductivity increases with the degree of saturation for a particular soil due to the low thermal conductivity of air compared to the thermal conductivity of liquid water, as shown in the following figure:

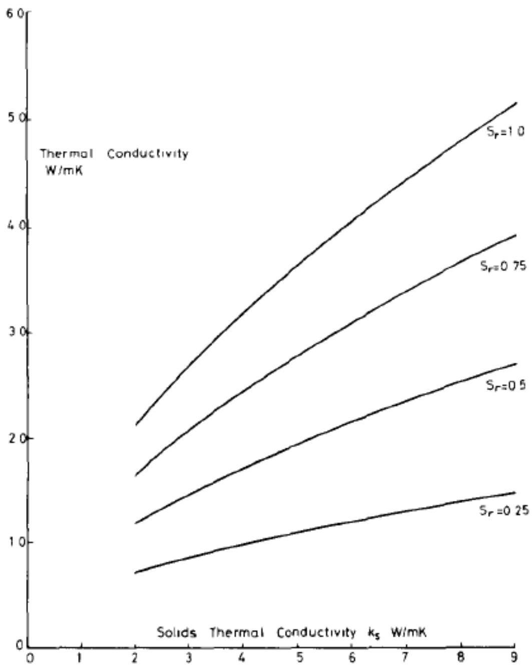


Figure 2-6 The change in the thermal conductivity of unsaturated soils in terms of the conductivity of dry soils and the degree of saturation (Faroukl, 1981).

It is clear from the last figure that the conductivity change is closely related to the chemical composition of the clay and the ions present in it. In general, the conductivity will decrease significantly with an increase in the clay's porosity percentage.

It was found that the temperature of the soil exposed plays a significant role in affecting the conductivity of the soil and the temperature change (periodic thermal loads)(Geng & Sun, 2018).

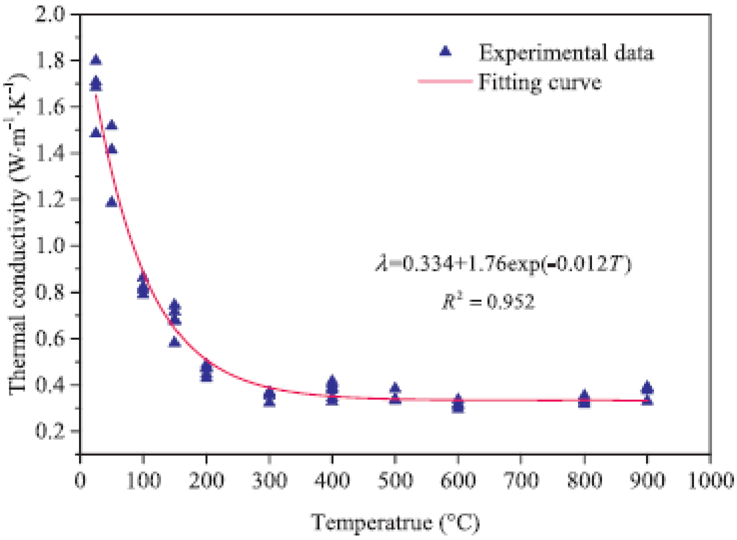


Figure 2-7 The change in the thermal conductivity of clay soils in terms of the temperatures they are exposed to during their history(Geng & Sun, 2018).

The following equation for determining the conductivity of clay soils in terms of temperature T [10].(Geng & Sun, 2018)

$$Kt = 0.334 + 1.7. e^{-0.012T} \qquad (2,9)$$

It was also found that a slight increase in the percentage of kaolinite clay leads to a significant improvement in the thermal conductivity values of non-cohesive soil.

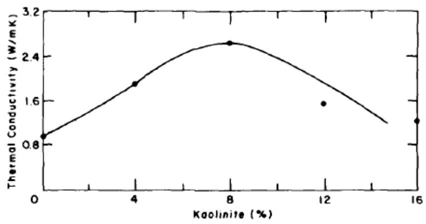


Figure 2-8 The change in the thermal conductivity of quartz with different percentages of kaolinite, where it was found that the preferred ratio is 8% to obtain the highest thermal conductivity(Faroukl, 1981.)

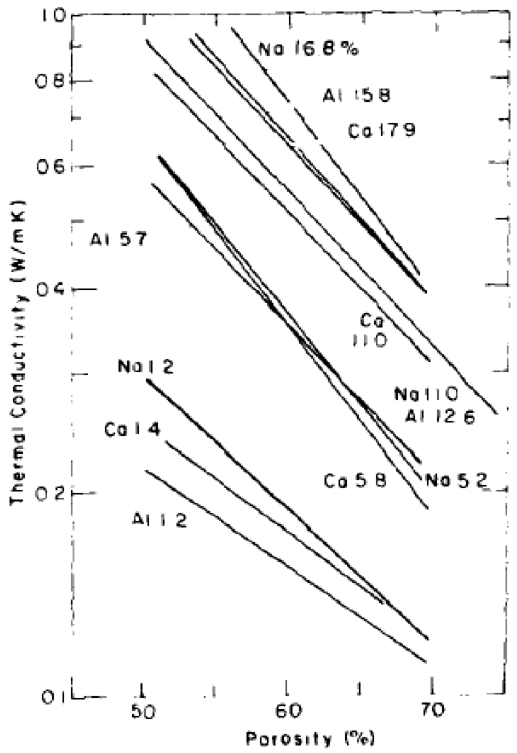


Figure 2-9 The change in the thermal conductivity of clay soils in terms of their porosity and according to the percentage of chemical mineral elements present within the clay [2]. (Faroukl, 1981)The figure shows the change in the thermal conduct

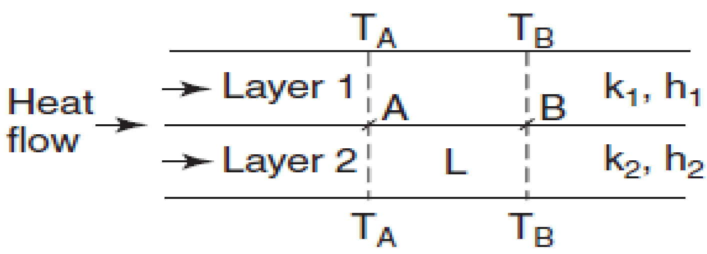


Figure 2-10 The equivalent thermal conductivity for horizontal layers of different thicknesses and conductivity of soil with heat flow in one direction only, which is the horizontal direction as shown in the figure(Briaud, 2013)

$$Ke = \frac{\sum Ki.hi}{\sum hi} \qquad (2,10)$$

$\boldsymbol{K}$e Equivalent conductivity of soil layers. $\boldsymbol{h1}$ thickness of the first soil. $\boldsymbol{h2}$ thickness of the second soil. $\boldsymbol{K1}$ Conductivity of the first soil. $\boldsymbol{K2}$ Conductivity of the second soil.

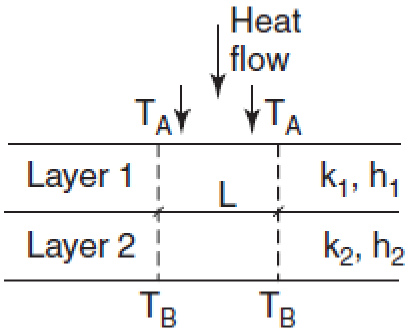


Figure 2-11 In the circumstance that the heat flow is vertical (i.e., from top to bottom), the following equivalency relationship is given:(Briaud, 2013)

$$Ke = \frac{\sum hi}{\sum \frac{hi}{ki}} \qquad (2,11)$$

$\boldsymbol{K}$e Equivalent conductivity of soil layers. $\boldsymbol{h1}$ thickness of the first soil. $\boldsymbol{h2}$ thickness of the second soil. $\boldsymbol{K1}$ Conductivity of the first soil. $\boldsymbol{K2}$ Conductivity of the second soil. (Wiley & Sons, 2013)

The effect of soil temperature is not limited to the thermal conductivity value but also affects other soil thermal properties, including diffusivity. Research has shown that the diffusivity value decreases under the influence of high temperatures of the clay soil.

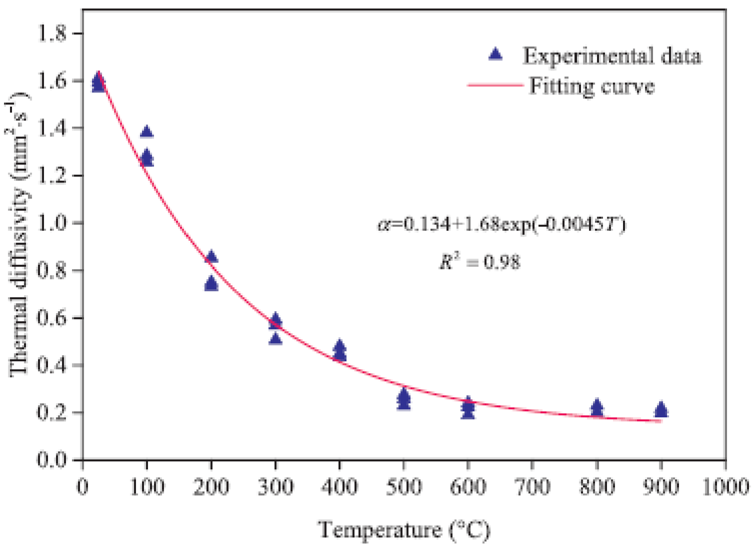


Figure 2-12 The change in the thermal diffusivity of clay soils in terms of the temperatures they are exposed to during their times (Geng & Sun, 2018).

The following equation for determining the diffusivity of clay soils in terms of temperature T [10].(Geng & Sun, 2018)

$$\alpha = 0.134 + 1.68.e^{-0.0045T} \qquad (2,12)$$

2.3 Thermal behaviour of the soil:

The thermal behaviour of clay soils under the influence of thermal loads is seen from the perspective of thermo-hydraulic mechanics, symbolised by the acronym (THM). Therefore, any temperature change will lead to changes in pore water pressure, soil porosity, liquid viscosity, and soil agitation. All the above is due to the thermal conductivity of the soil, and although there is an effect of convection within the ground, its effect is almost non-existent (Wieczorek et al., 2017).

The transfer of heat through the thermal conductivity of the soil, which leads to a change in viscosity and thus the emergence of pore water pressure, which leads to the changing in the temperature of the soil mass will lead to an essential change in both the viscosity of the water contained within the soil pores and the density of this water (therefore, the water suffers from volume expansion or volumetric contraction of the water mass), which in turn leads to changes in pore water pressure and changes In the stresses applied to the soil grains, it is known that the density of distilled water at a temperature of 4^{0} is 1000 kg/m3. Still, a change in water temperature leads to a change in this density in a non-linear manner. The same applies to the viscosity of water. The relationship is non-linear concerning the temperature change.(Bergström, 2017).

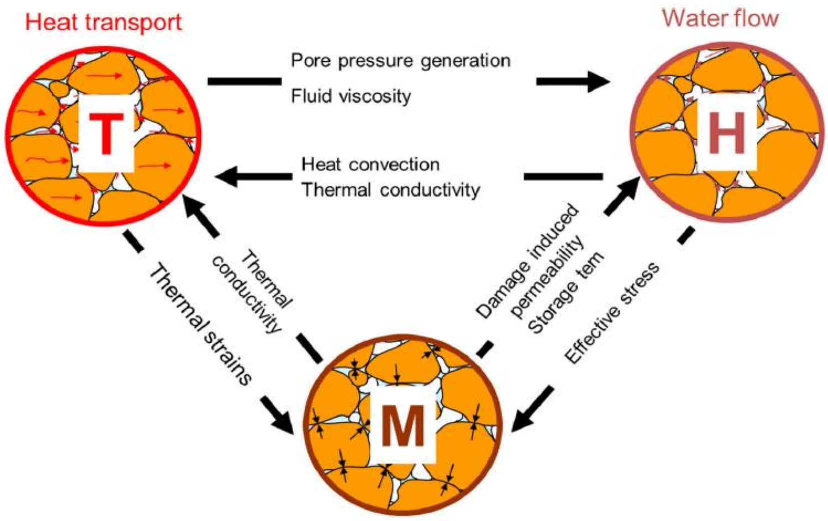


Figure 2-13 The hydraulic thermomechanical effect of clayey soils (Wieczorek et al., 2017).

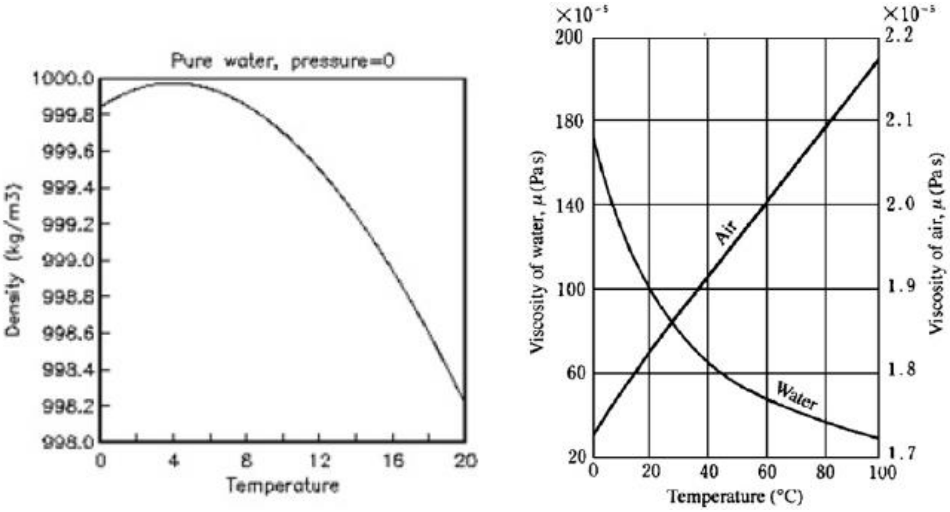


Figure 2-14 The change in the density and viscosity of water with the change in temperature (Bergström, 2017).

2.4 One-dimensional heat flow in soils:

The finite earth element of dimensions dx,dy, whose thermal conductivity is K. This element is subjected to a heat flow from the surface with the highest temperature to the lowest temperature(Wiley & Sons, 2013). It is shown in the figure:

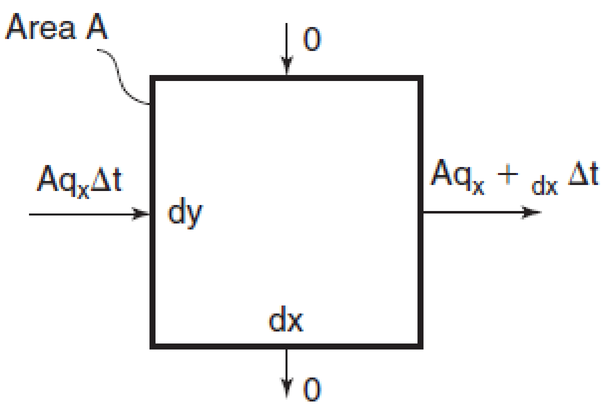


Figure 2-15 The highest temperature to the lowest temperature (Wiley & Sons, 2013)

As a result of heat transfer, the soil element will retain a portion of the transferred energy of DQ, equal to the difference in the amount of heat between the two surfaces.

$$dQ = Aq_x dt - Aq_{x+dx} dt \qquad (2,13)$$

According to the law of heat transfer :

$$q = K.\frac{dT}{dx} \tag{2,14}$$

On the other hand, the amount of heat transferred is equal to:

$$dQ = m.c.\Delta T = A.dx.\rho.C.\Delta T \tag{2,15}$$

Equally between the two previous equations:

$$\mathrm{A.dx.\rho.C.\Delta T = Aq_x dt - Aq_{x+dx} dt} \tag{2,16}$$

And after fixing:

$$\frac{dq}{dx} = \rho.C.\frac{dT}{dt} \tag{2,17}$$

Then it can see that:

$$\frac{d^2T}{dx^2}.K = \rho.C.\frac{dT}{dt} \tag{2,18}$$

The diffusivity is given by the following equation:

$$\alpha = \frac{Kt}{C.\rho} \tag{2,19}$$

By reforming, it get the following differential equation that expresses heat flow in a single direction:

$$\frac{d^2T}{dx^2} = \frac{1}{\alpha}.\frac{dT}{dt} \tag{2,20}$$

Assuming that the heat flow is three-dimensional, the equation becomes as follows:

$$\frac{d^2T}{dx^2} + \frac{d^2T}{dy^2} + \frac{d^2T}{dz^2} = \frac{1}{\alpha}.\frac{dT}{dt} \tag{2,21}$$

The previous equations are solved by knowing the conditions of the beginnings and the thermal ends. Numerical methods such as the finite element and peripheral element methods can be used.

The hydraulic conductivity factor of the soil (symbolised by K) depends on the permeability of the soil and the properties of the liquid (water) (viscosity and density), and the grain gradient of the soil, so the heat flow is modelled by similar equations to the flow of water within the soil. (Wiley & Sons, 2013)

2.5 Effective stresses and pore water pressure:

The pore water pressure describes the pressure of the water filling the voids surrounding the soil particles, u, given in the formula below as the sum of the static and excess water pressure in the pores.

$$\sigma' = \sigma - u \qquad (2,22)$$

When soil is loaded or unloaded, a difference in pore pressure will occur, which affects the effective strains

Temperature changes in low-permeability clays usually lead to increased pore water pressure. In geothermal Pile systems, it is generally overlooked because most installations occur in soils with higher permeability values. In low permeability soils, these temperature increases can increase pore water pressures and reduce effective stress(Bergström, 2017).

In the presence of low permeability clay soils, the excess pore water pressures can reach in the range of 1Mpa at the temperature change of 30°C, which in most practical cases of thermal Pile exceeds the actual pressure at the contact surfaces.

When the clay is cooled or heated, the pressure of the generated pore-water depends on the amount of water absorbed and the volume difference of the clay as a result of the thermal change in the drained conditions and the pressure of the pore water generated within the clay(Zeinali et al., 2020).

2.6 Volumetric thermal expansion factor:

The effects of temperature on the properties of clay soils have been studied experimentally by several researchers by conducting isothermal linear scale tests at different temperatures all of whom observed a decrease in pre-tightening pressure with increasing temperature (Sultan et al., 2001).

A linear decrease in pre-tightening pressure with temperature was observed from the tests carried out between 0 and 50 °C on four different types of clay from the Site (fluidity limits of 40 and 120).

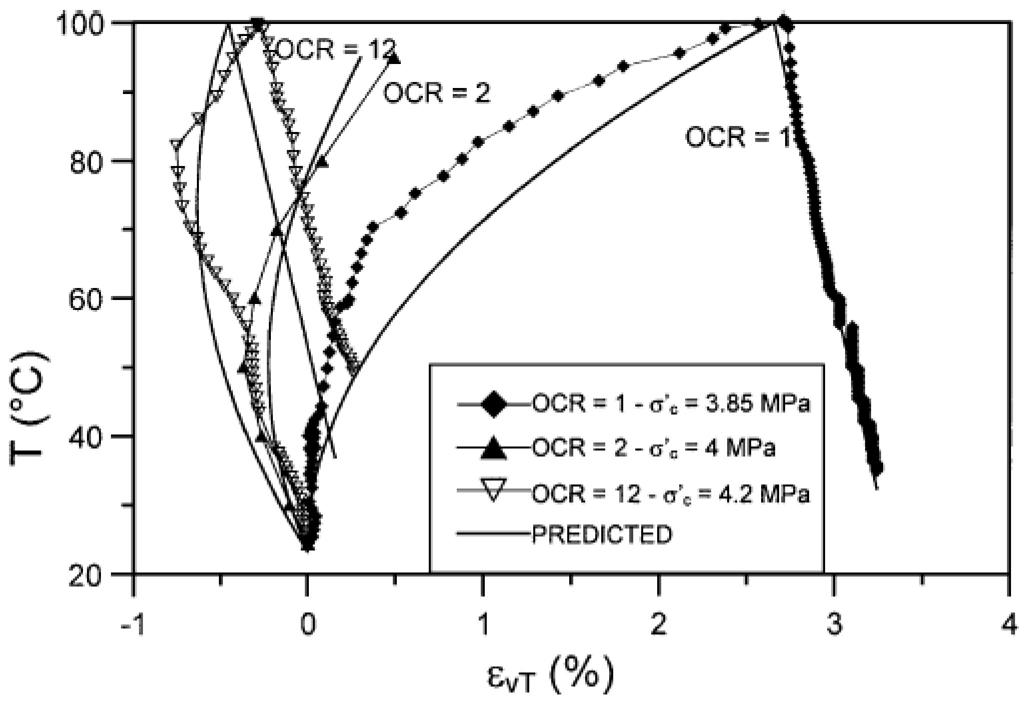


Figure 2-16 The change in the volumetric expansion factor of different types of pre-stressed clay at different temperatures(Sultan et al., 2001).

2.7 An example of heat transfer within soils: The case of a thermal pile system:

As an example of the behaviour of the soil under the influence of the thermal loads of the soil and the thermal conductivity of the soil, a thermal heating system based on thermal energy Piles can be studied, which are piles that serve as the foundations of the facility (as shown in the following two figures) that provide a water flow circuit to secure heat transfer with the soil surrounding the pile and benefit from this The system in residential heating buildings during the winter(V.-T. Nguyen, 2019).

It is also used to cool buildings during the summer. The amount of energy obtained from the soil surrounding the piles is about 75% of the energy needed for heating.

This type of system has been used since 1980 in Europe; then, it has been used in many countries such as the United States of America, Switzerland, and Austria.

Seasonal ground temperature in cold regions remains relatively constant below 10-15 m depth and is about ten °C and 15°C at a depth of about 50 m (V.-T. Nguyen, 2019).

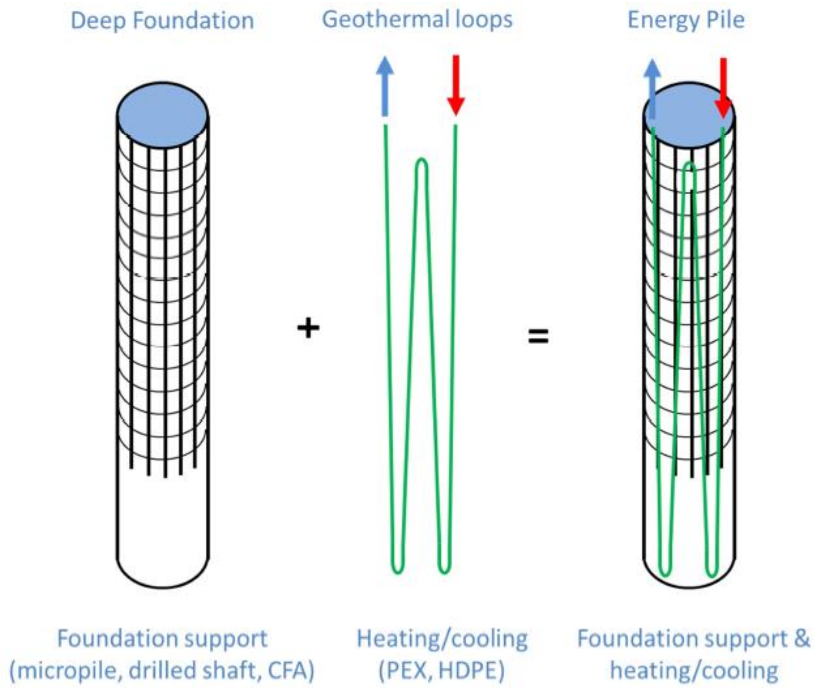


Figure 2-17 The pile with its structural reinforcement and the heat exchange circuit of polyethene pipes(V.-T. Nguyen, 2019).

Polyethene pipes are placed within the section of the pile in addition to reinforce the pile, where water enters (as shown in the previous figure) with a certain degree of gravity and exits from the other end after heat exchange occurs with the pile material and with the soil surrounding the pile. The low-temperature ground can cool the building in summer, while high-temperature soil is suitable for heating the building in winter, ideal in cold areas.

Usually, one building is provided with several piles that secure its thermal needs (as shown in the following figure). These piles are connected with the heating system to form an integrated approach with the soil under the building.

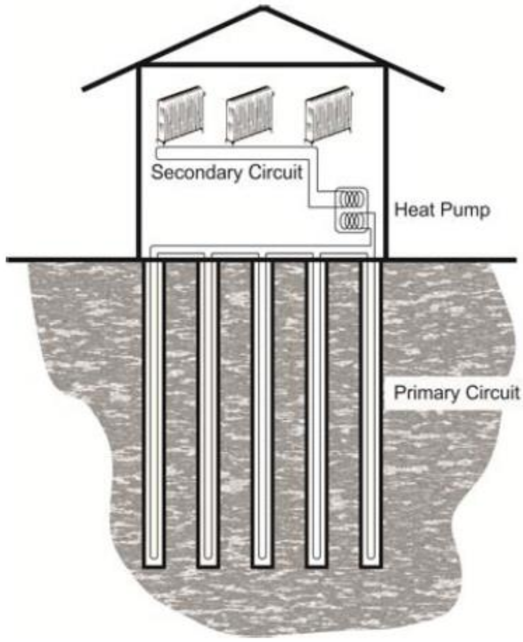


Figure 2-18 Building with thermal piles attached to heating system (Loveridge et al., 2018).

This heating system has several advantages, including reducing the amount of energy used, reducing the amount of carbon dioxide emitted, reducing noise, and ensuring sustainability in the investment of available energy sources. Therefore, it can be considered a clean energy source as it is regarded as renewable.

3 Methods

3.1 The analytical solutions:

Several analytical and theoretical explanations have been proposed to simulate heat transfer by conduction through the thermal system consisting of piles and pipes through which water and surrounding soil pass. Most of these solutions and models assume several assumptions to simplify the solution, the most important of which are:

• Heat transfer occurs through conduction only.

• The environment is homogeneous and infinite.

• The initial temperature is constant.

• Earth's surface temperature is negligible.

• Heat transfer occurs horizontally, and vertical heat transfer is negligible.

• The rate of heat flow through the tubes within the pile is constant.

The analytical models are generally divided into two main types, the first depending on heat transfer through homogeneous media. In contrast, the second type relies on the assumption of heat transfer through compound media (heterogeneous)(V.-T. Nguyen, 2019).

And the temperature must be constant once the thermal system starts working, meaning that the pile’s length must be much greater than the diameter of the pile, meaning that the instantaneous heat transfer is not essential.

There are many assumptions in determining the heat source model, including:

1- **Linear heat source model:** It is assumed that there is a linear heat source through which a constant heat flow q passes that lead to a change in temperature in the soil of ΔT over a time t, and the following relationship expresses it:

$$\Delta T_g = \frac{q}{4\pi K}\int_{r^2/_{4\alpha t}}^{\infty} \frac{e^{-u}}{u}du = \frac{q}{4\pi K}\left(\ln\left(\frac{4\alpha t}{r^2}\right) - \gamma\right) \quad (3,1)$$

The change in the temperature of the liquid ΔT_f is given by the following relationship:

$$\Delta T_f = qRb + \frac{q}{4\pi K}(ln(4Fo) - \gamma) \quad (3,2)$$

$\boldsymbol{\gamma}$=0.557 Euler constant and $\boldsymbol{F}$Fauret constant $\boldsymbol{Rb}$ Thermal resistance factor $\boldsymbol{K}$ Thermal conductivity factor of the soil $\boldsymbol{\alpha}$ Thermal diffusivity of the soil (Loveridge et al., 2013).

2- **Finite cylinder heat source model**: In this case, instead of assuming that the heat source behaves linearly, the heat source is considered a finite hollow cylinder, and this model expresses heat transfer better than the previous model and the p, previous equations become as follows:

$$\Delta T_g = \frac{q\,G}{4\pi K} \quad (3,3)$$

G is a function of the immediate number

$$G = \frac{2}{\pi}\int_0^{\infty} f(\beta)d\beta \quad (3,4)$$

3- **The oscillating heat source model**: in the previous models, it was assumed that the heat flow applied to the thermal system is constant, which does not correspond to reality. Therefore, in this model, the change in heat flow was considered.

In most of the previous models, solutions to the existing functions are reached through the numerical methods of the integrals to determine the function G:

$$G\left(\frac{t}{t_s},\frac{r_b}{H}\right) = \begin{cases} \ln\left(\frac{H}{2r_b}\right) + \frac{1}{2}\ln\left(\frac{t}{t_s}\right); \frac{5r_b^2}{\alpha} < t < t_s \\ \ln\left(\frac{H}{2r_b}\right) \end{cases} ;t > t_s \quad (3,5)$$

$$t_s = \frac{H^2}{9\alpha} \quad (3,5,1)$$

It is the time required to reach a homogeneous temperature and ranges between days and years(V.-T. Nguyen, 2019).

3.2 Modelling using the finite element method:

The finite element method was used to determine the thermal behaviour of the soil as it'll as to model thermal systems.
The plaxis 2d program is considered one of the essential software in geotechnical engineering, which is based on the theory of finite elements and is used to determine the descents and the critical bearing capacity of piles (including thermal Piles) and surface foundations. For piles and on the hydrothermal properties of the soil.
To design an accurate case model using Plaxis, it is essential to understand how to draw the model and enter dimensions in Plaxis it offers two methods for determining dimensions:

3.2.1 Axisymmetry

Axisymmetry is suitable for determining circular models with specific diameters. The researcher works in the cross-section defined by the y-axis and the x-axis, but the program will consider the direction out of the plane (z), assuming that all strains are equal in the two directions εx = ε z (Tjie-Liong, 2014).

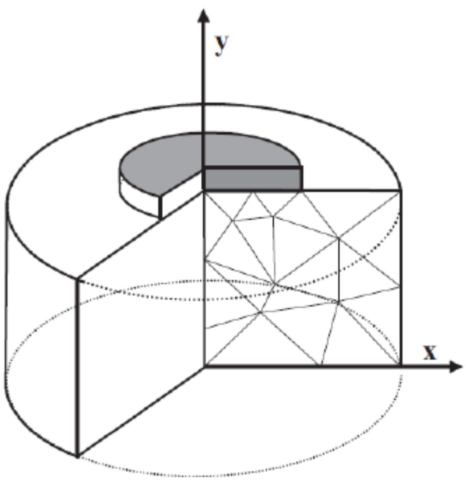


Figure 3-1 The model's dimensions using the Plaxis program using the Axisymmetry method (Maarouf, 2019).

3.2.2 Plane Strain:

Plane strain is used for cases where the segment is regular outside the studied plane. This option is often used to model extended roads or excavations with greater length than width.

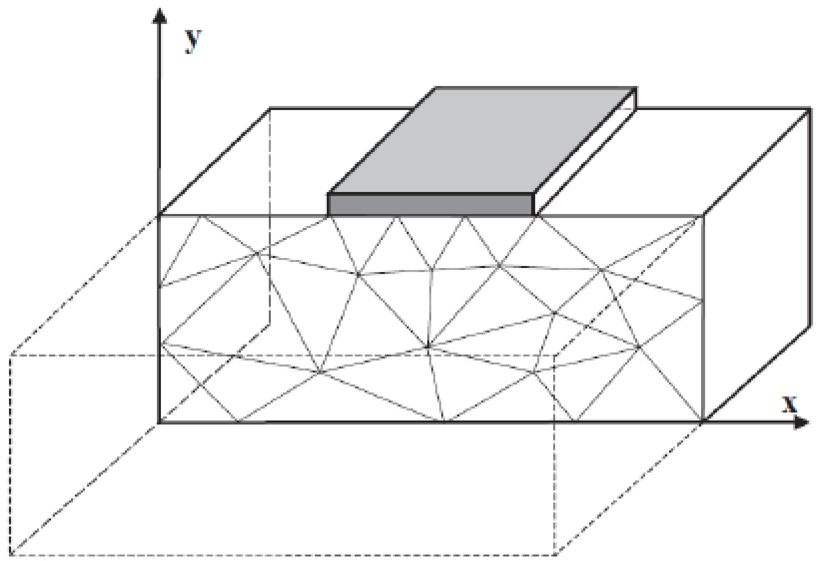


Figure 3-2 Dimensions of the model using the Plaxis program by using the Plane Strain method (Brinkgreve et al., 2011)

3.3 Material model:

The mechanical behaviour of soils and rocks can be modelled with varying accuracy, so plaxis 2d suggests several models. These models have been proposed based on many experiments and studies of soil behaviour (Plaxis V20, 2020).

3.3.1 Linear Elastic model (LE)

This model depends on Hooke's law for homogeneous behaviour of materials that is, the relationship between strain and stress is linear. The required model parameters are E, the soil's Young's modulus and Poisson's ratio μ (Brinkgreve, 2004). Although grounds generally do not follow this behaviour, it is suitable for initial simple modelling to understand the global response of the system before moving to a more advanced modelling.

3.3.2 Modified Cam-Clay model (MCC)

This model is based on the critical state theory of the soil. It is able to capture the elastoplastic soil behaviour reasonably well. The yield surface of MCC is shown in Figure 3-3. The details of the model is out of the scope of this thesis but the interested reader can consult Plaxis2D material models manual for full details.

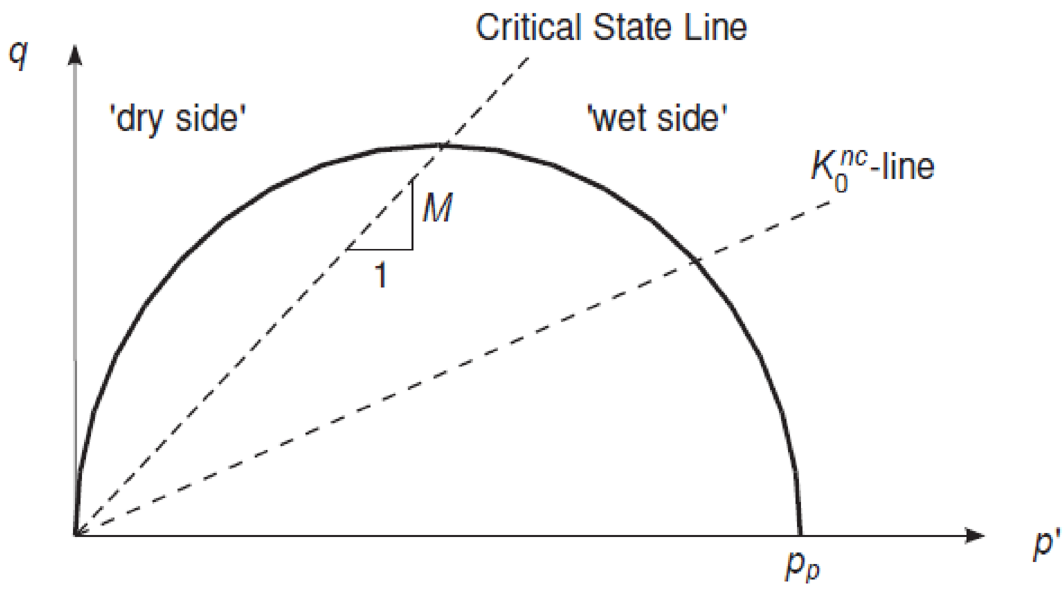


Figure 3-4 Modified Cam Clay yield surface (Brinkgreve, 2004).

3.4 Numerical modelling using Plaxis2D finite element:

This program works within a windows environment and relies on the finite element method to analyse and study the deformations of soils and rocks under the influence of different loads and soil structures. The plaxis 2D program consists of four main programs, which are, in order:

3.4.1 Input step:

The stage of work within this program is the pre-treatment stage, which is used to enter the primary data necessary to describe the issue under study. It includes determining the dimensions and shape of the engineering model, introducing the characteristics of the various materials composing the model, defining the effective loading system, and determining the boundary conditions and the initial conditions for the studied issue, including groundwater.

3.4.2 Calculation step

Calculation and processing program the specific point of this program is that it enables accurate and accurate modelling of the different stages of project construction, which helps to calculate the stresses and distortions of each step separately.

3.4.3 Output step:

It is a post-processing stage concerned with outputting the results of the calculations, as it presents the studied finite element network model and the stresses affecting it in its various forms. The program also provides the ability to display the results in tables.

3.4.4 Curves program:

A program is used to display the relationship's curves between the loads-deformations, the relative stresses-strains, and the paths of stresses and deformations at selected points of the engineering model and the possibility of displaying the distribution of groundwater pressures.

4 Analysis

When performing the numerical analysis process, it will review the properties of the soil and the Pile used in the numerical study and the soil models used in this research, where the characteristics of the soil and the Pile and its dimensions and the dimensions of the model used are adopted based on the experimental study in which the numerical model was simulated on the Plaxis 2D thermal program. The temperature function was taken from the study's Experimental and comparison results.

A metal pile model with a length of 28.8 m was applied within a soil model with dimensions (Xmin=0, Xmax=5.7m) and a soil depth of 40m. The surface of a water rug was placed at a depth of 1m below the surface of the earth and with an initial temperature of the earth 8.5c, which is equivalent to 283k, and the soil model with its dimensions is shown in figure (4-1).

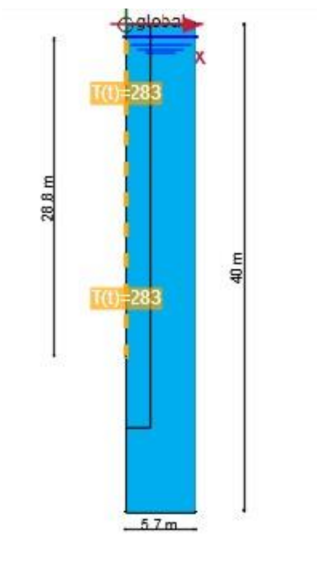


Figure 4-1 Geometry of the simulated example

The axisymmetric model was chosen because the Pile used in the model is circular with a radius of 0.057m, and this model is suitable for it in this case. A model with 15 nodes was also chosen, where the finite element method program allows modelling with 12 and 15 knots. In our case, 15 elements are selected. They represent the most accurate condition the mesh has been placed very fine during all processes to obtain more accurate results.

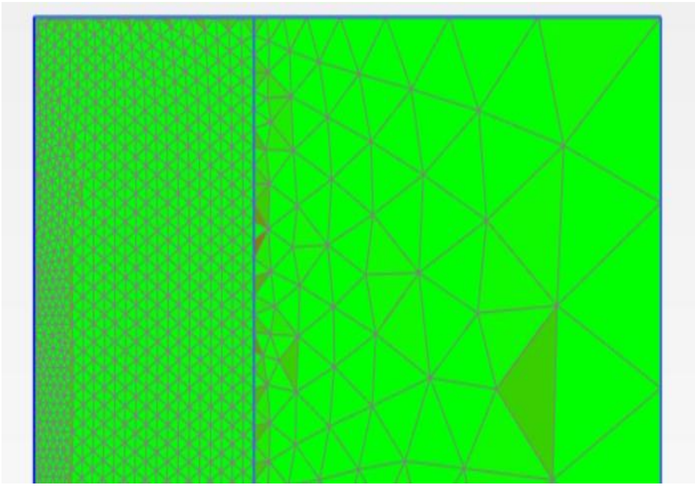
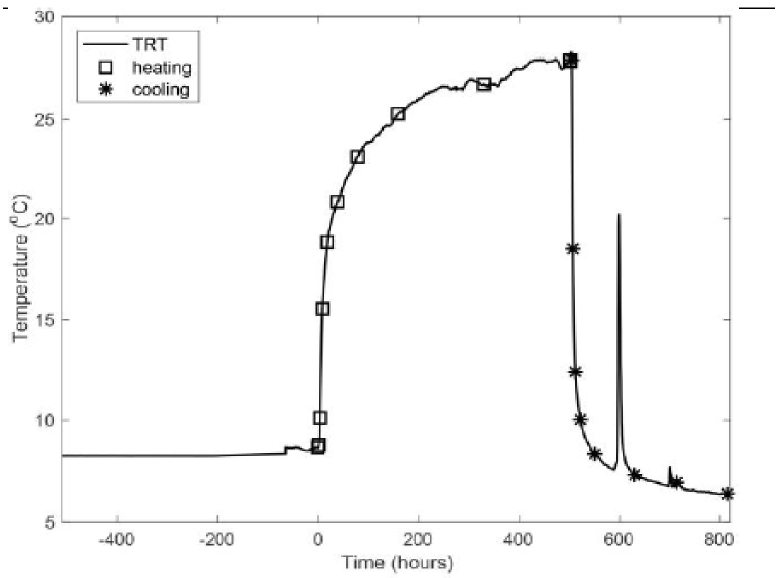


Figure 4-The simulated example by using the mesh option very fine

The temperature parameter (heating for 21 days and cooling within 13 days) was taken, i.e., a follower with a total of 34 days from the pilot study. It relied on the drawn curves in terms of temperature and time, estimated in hours.



Figur 4-2the The curve express the colling and heating process in experimental study (Bergström, 2017)

From this curve, the drawn points are withdrawn and converted into a function applied in the program, representing the heating and cooling processes within several hours of heating and cooling. This function was adopted during all the studied analysis processes.

Table 4-1 The function was adopted during all the studied analysis processes.

#	Time[day]	ΔTemperature[K]
1	0.0000	0.000
2	0.11820	1.631
3	0.35461	7.003
4	0.76832	10.31
5	1.5957	12.31
6	3.1915	14.54
7	6.4421	16.71
8	13.416	18.13
9	20.508	19.26
10	20.686	9.999
11	21.040	3.904
12	21.336	1.562
13	22.459	-0.09091
14	25.709	-1.193
15	29.078	-1.606
16	33.156	-2.157

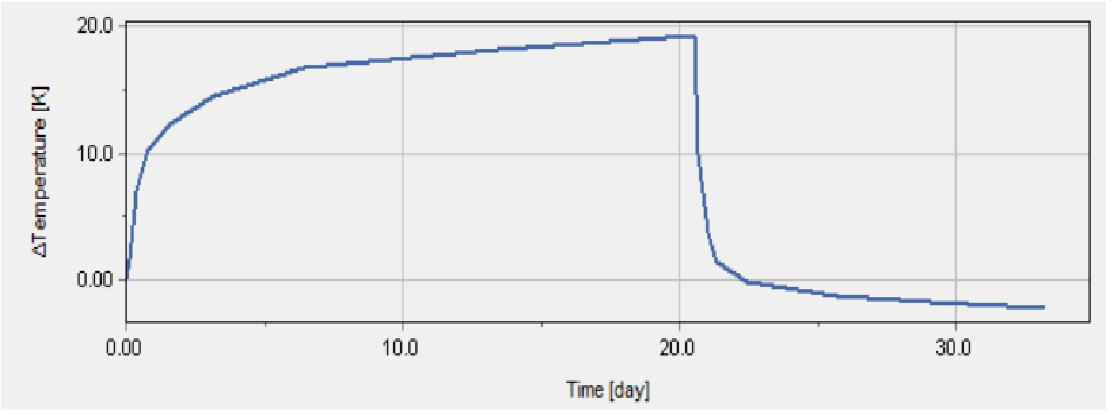


Figure 4-1 The curve of thermal function in Plaxis2D

4.1 Parameters of the soil and pile used in the research:

The soil used in the study is clay soil, which is wide distribution in most regions of Sitten in the Utby. The Pile is modelled from steel material, with a length of L=28.8 m and a diameter. The following table shows the parameters of the soil applied in the model.

Table 4-1 roperties for the layer by using the linear elastic model in Plaxis 2D:

Property	Unit	Value
E'	$kN\ /\ m^2$	7500
v' (nu)		0.200
G	$kN\ /\ m^2$	3750
E_{oed}	$kN\ /\ m^2$	7500
Velocities		
V_s	m/s	47.36
V_p	m/s	66.98
Material set		
identification		Clay
Material model		Linear elastic
Drainage type		Drained
color		RGB 161,226,232
comments		
General properties		
Y_{unsat}	$kN\ /\ m^3$	16.40
Y_{sat}	$kN\ /\ m^3$	16.40
parameters		

C_s	$kJ / t / K$	3300
λ_s	$kW / m / K$	1.180E-3
$\boldsymbol{\rho}_s$	t / m^3	1.640
Solid thermal expansion		Volumetric
a_s	1 / K	0.02500E-3
D_v	m^2 / day	0.000

Table 4-2 Properties for the layer by using modified cam clay model in Plaxis 2D

Identification	Units	clay
Undrained behaviour		Standard
Stiffness		Standard
Strength		Rigid
R_{inter}		1.000
Consider gap closure		yes
Real interface thickness		
δ_{inter}		0.000
Groundwater		
Cross permeability		Impermeable
Drainage conductivity, dk	m^3/day/m	0.000
Thermal		
R	m^2 K/kW	0.000
C_{ref}	kN/m^2	10.00

Φ(phi)	°	20.00
ψ(psi)	°	0.000
K_0 determination		Automatic
$K_{0,X} = K_{0,Z}$		Yes
$K_{0,X}$		0.6577
$K_{0,Z}$		0.6577
Overconsolidation		
OCR		1.450
POP	kN/m²	0.000

Flow parameters		
Use defaults		None
K_x	m/day	0.08000E-3
K_y	m/day	0.08000E-3
$-\psi_{unsat}$	m	10.00E3
e_{init}		2.050
Parameters		
Solid thermal expansion		Volumetric
α_s	1/K	0.04000E-3
D_v	m^2/day	0.000
f_{Tv}		0.000

Table 4-3 Properties for the pile in Plaxis 2D

Property	Unit	Value
Material set		
Identification		Pile
Colour		RGB 0,0,255
Material type		Elastic
Isotropic		✔
EA_1	kN/m	5.000E6
EA_2	kN/m	5.000E6
EI	kNm^2/m	9000
d	m	0.1470
w	kN/m/m	0.000
v(nu)		0.2000
Rayleigh α		0.000
Rayleigh β		0.000

4.2 Analysis stages:

4.2.1 Comparison between the experimental study and the numerical study for temperature:

A Linear Elastic soil model was used. This model is considered the most simplified model for simulating soil, considering that the soil has a linear elastic behaviour. The heat distribution in the soil was studied from the area near the Pile up to a distance of 5.7 m, and the results are compared with the experimental study previously studied during this stage. Several parameters of the thermal properties changed, and the effect of this change on heat diffusion was studied.

4.2.2 Comparison between the different models:

At this stage, the soil model was changed to Modified cam clay, and this model expresses the soil in the state of collapse (critical condition). This stage represents the volume stability with the continuation of the strain in the critical state stage. The comparison is made between the soil in a linear state and the case of collapse and the effect of this model on the heat distribution inside the ground in the area around the pile.

4.2.3 Studying the effecting of load on temperature

At this stage, a point load of 90 KN was applied to the Pile, as shown in the figure, to study the effect on the behaviour of heat distribution in the ground during the heating and cooling processes.

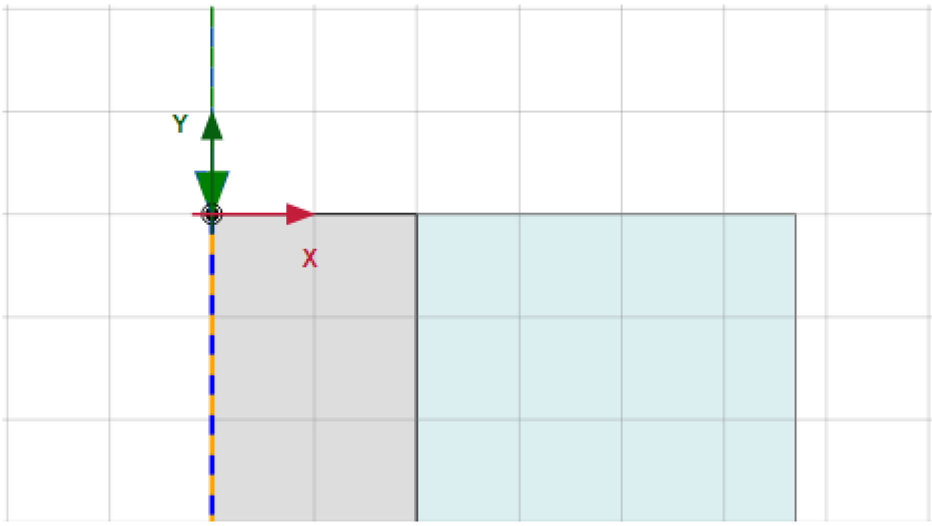


Figure 4-2 the figure shows the point load that is applied to the pile.

4.2.4 Comparison between the experimental study and the numerical study for excess pore water pressure kpa:

At this stage, the value of the excess pore water pressure obtained in the soil at different temperatures during the heating and cooling processes was studied. The numerical study results are compared with the results obtained from the experimental study.

5 Results

In the first stage the heating phase with linear elastic mechanical behaviour as resulted from the numerical study and compare it with the experimental study for different time intervals during the heating phase starting by the first hour of the heating phase until the end of heating on day 21, and the following curves show these results.

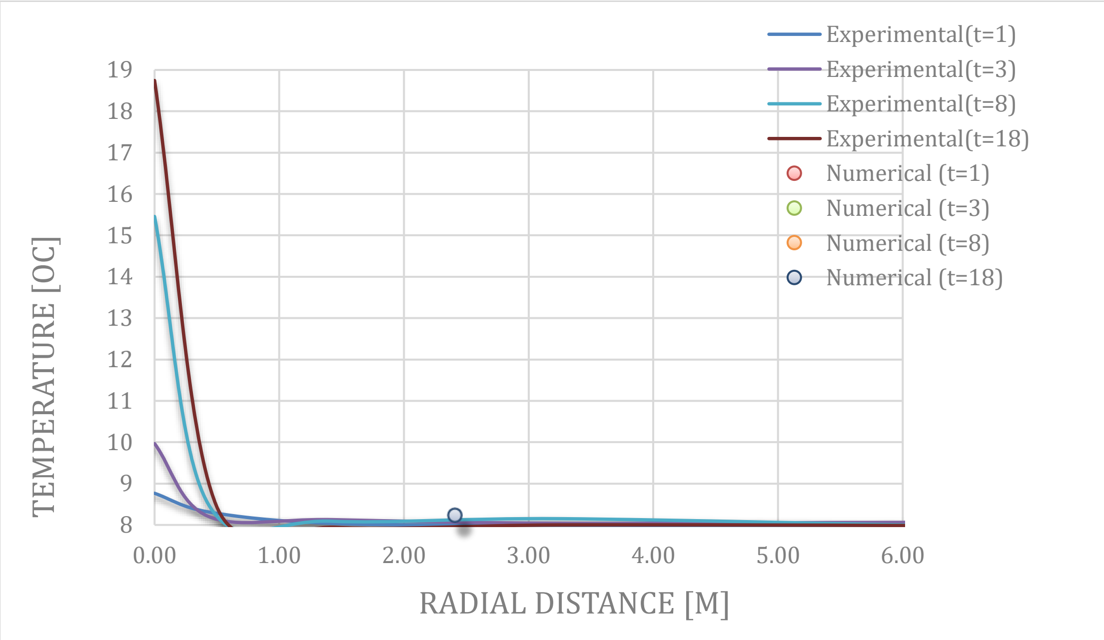


Figure 5-1 expresses the relationship between temperature and the relative distance from the pile starting from 1 h until 18 h

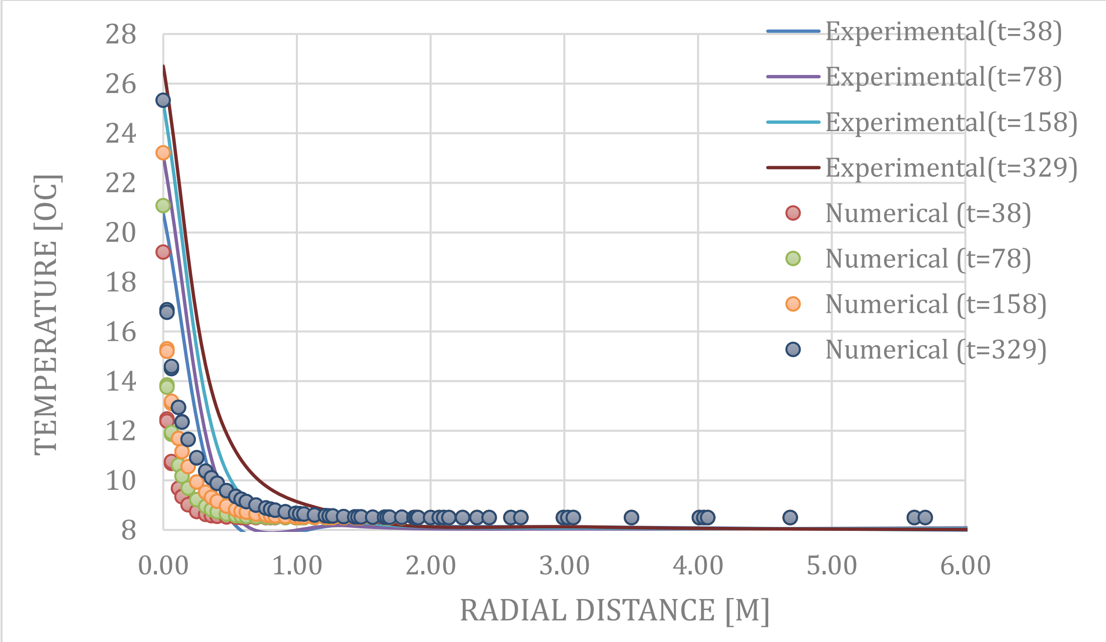


Figure 5-2 expresses the relationship between temperature and the relative distance from the pile starting from 38 h until 329 h

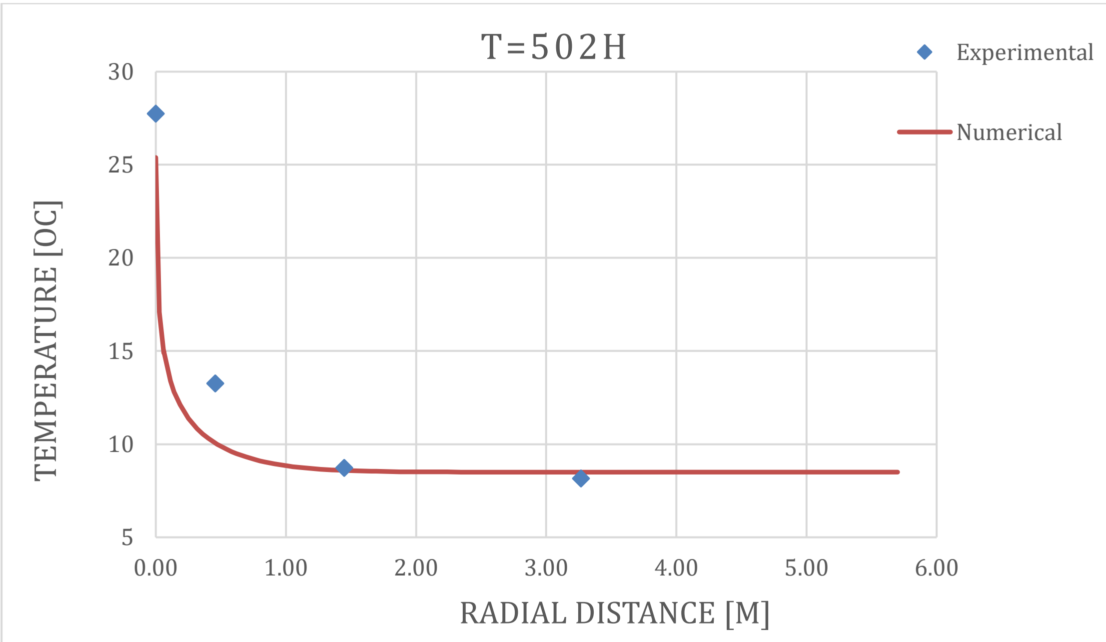


Figure 5-3 expresses the relationship between temperature and the relative distance from the pile at 502 h

The numerical results are also compared with the field measurements in the cooling phase at (t=629h,814h), that is, in the middle and at the end of the cooling stage, and the comparison with the experimental study extended for 13 days, from the end of the heating stage until the end of the cooling so that the total time for the two stages is 34 days as it is shown in the following two curves.

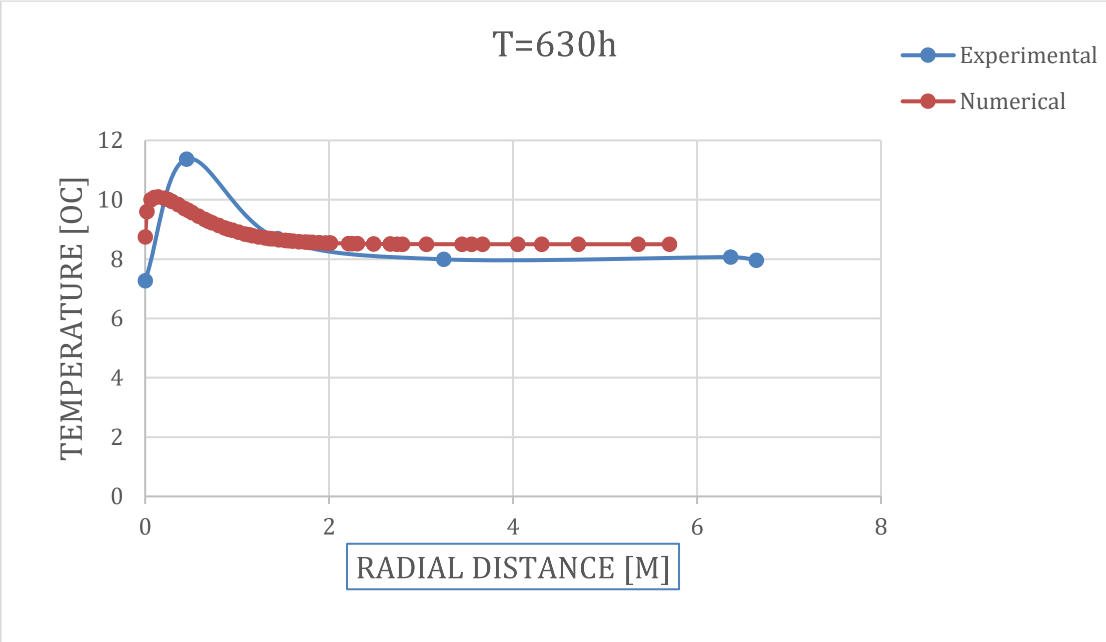


Figure 5-4 expresses the relationship between the temperature and the relative distance from the Pile at 630 h

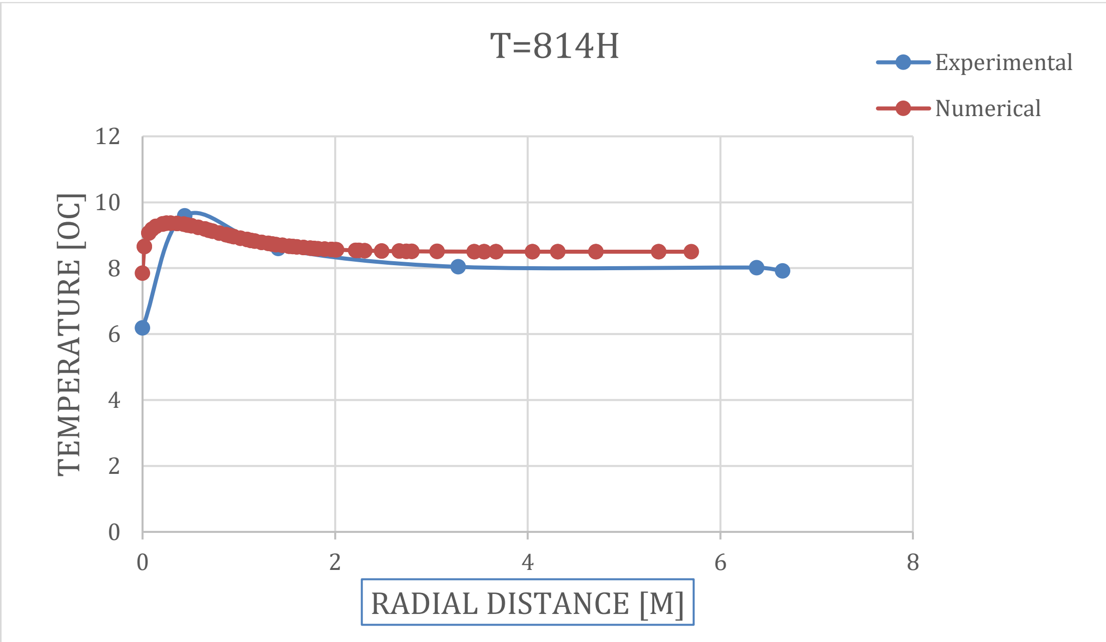


Figure 5-5 expresses the relationship between temperature and the relative distance from the Pile at 814 h

To study the effect of the thermal properties, firstly, the heat capacity was varied within the permissible range of values (3300-3400) kj/t/k. This factor was adopted from the experimental study. The effect of this factor on heat distribution in the heating stage was studied, and the results are compared between the two previous values and shown in the following curves

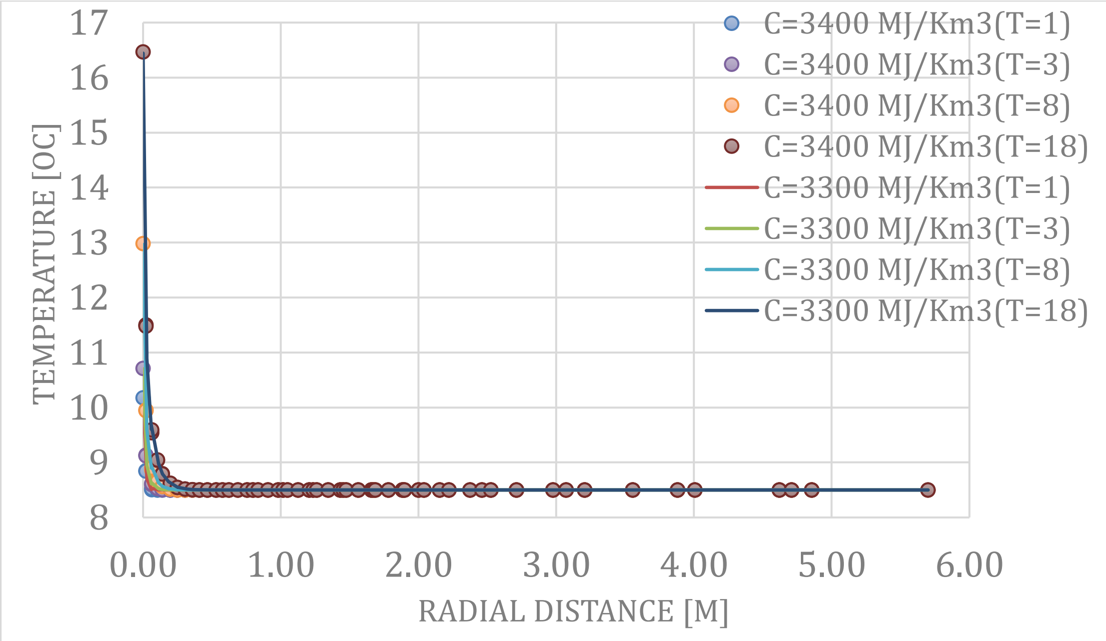


Figure 5-6 expresses the relationship between the temperature and the relative distance from the Pile starting from 1 h up to 18 h by changing the heat capacity values.

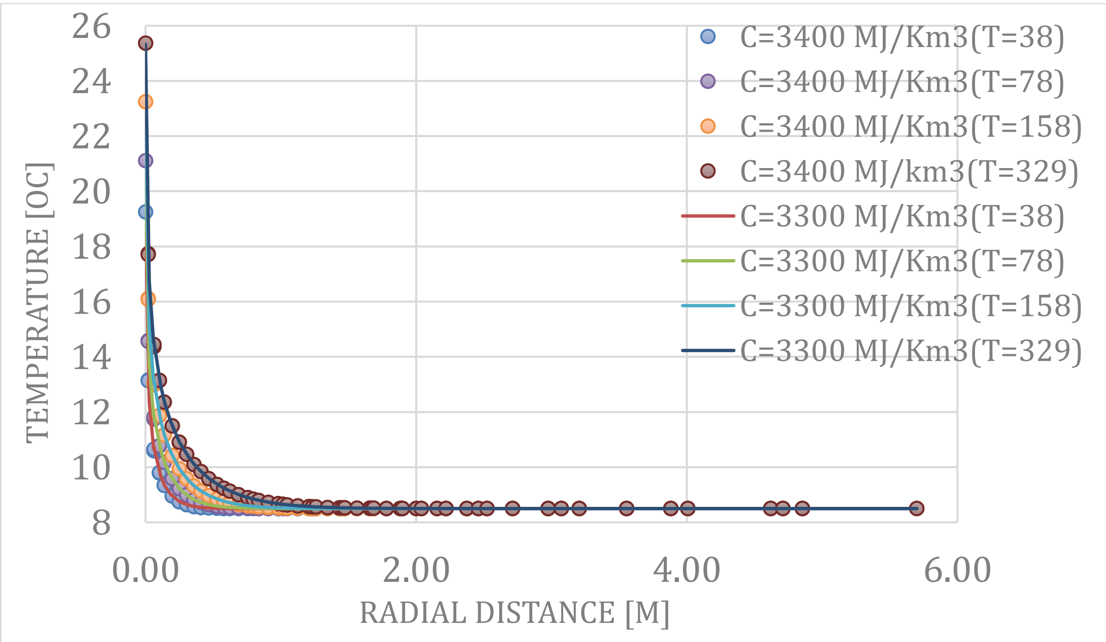


Figure 5-7 expresses the relationship between the temperature and the relative distance from the Pile starting from 38 h up to 329 h by changing the heat capacity values.

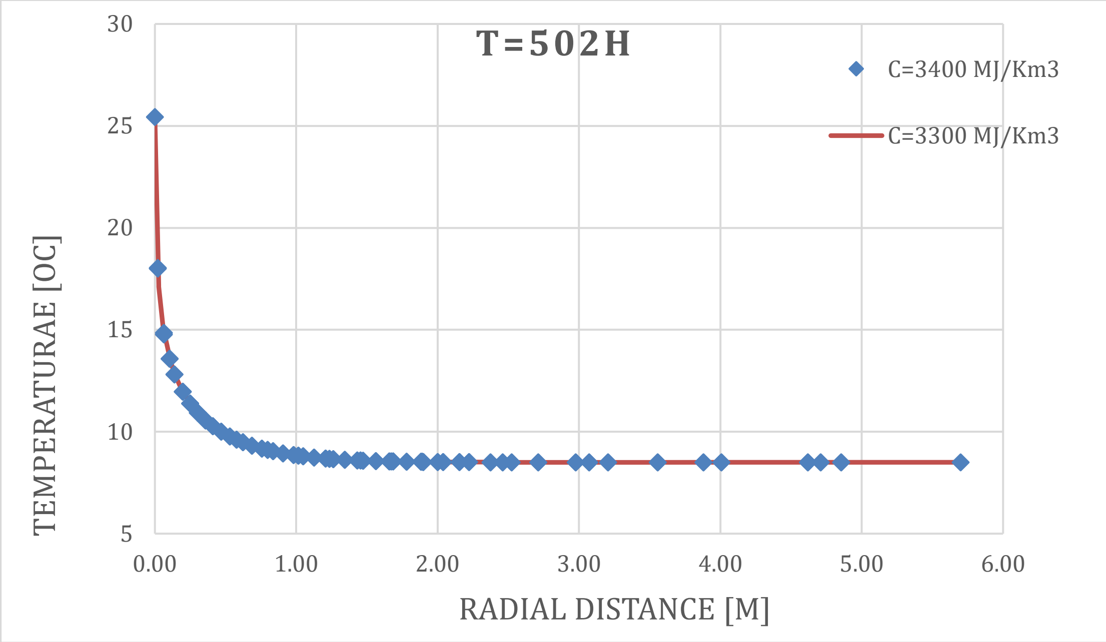


Figure 5-8 Expresses the relationship between temperature and the relative distance from the Pile at 18h at 502h by changing the heat capacity values.

The same comparison was made for the cooling phase as in the following curves during the times (t=630h,814h).

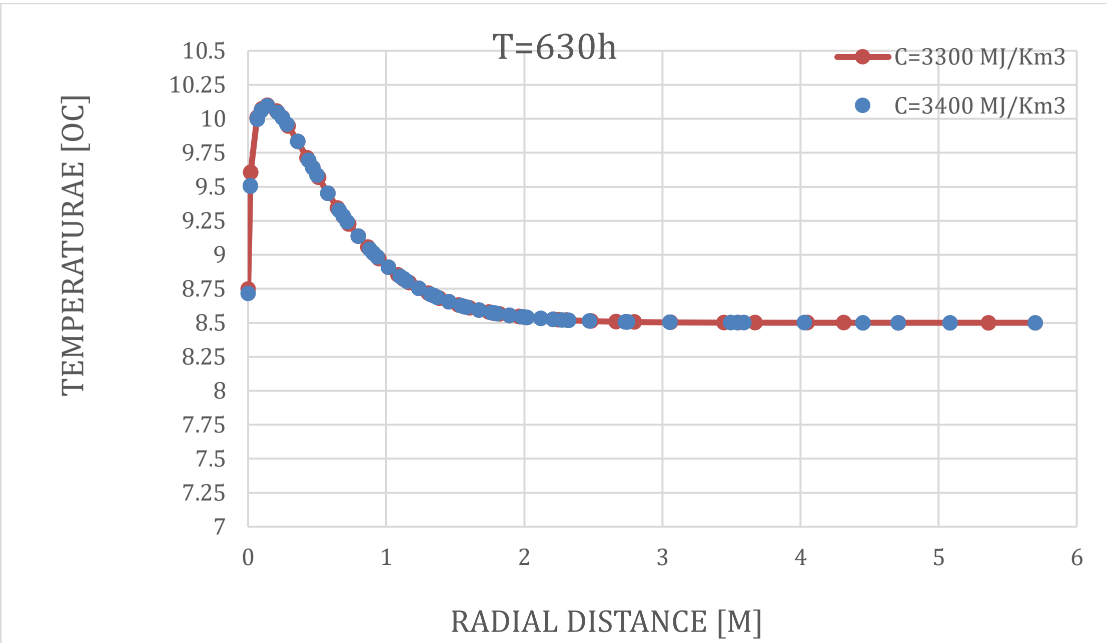


Figure 5-9 Expresses the relationship between the temperature and the relative distance from the Pile in the middle of the cooling phase at 630 h by changing the heat capacity values.

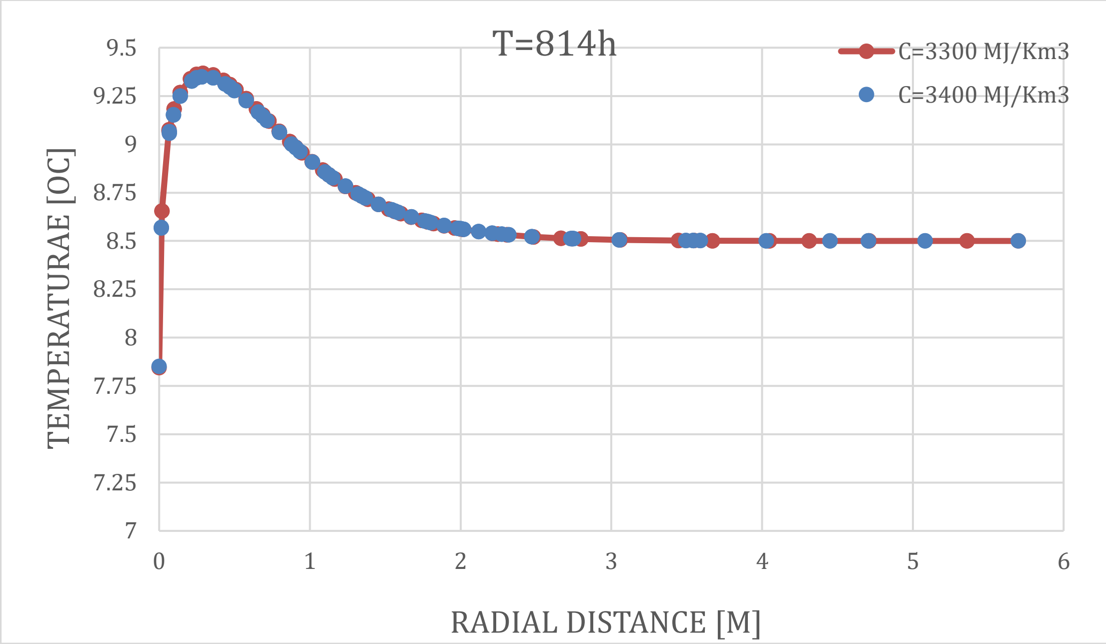


Figure 5-10 Expresses the relationship between the temperature and the relative distance from the Pile at the end of the cooling phase at 814 h by changing the heat capacity values.

Among the basic thermal properties, the change in the thermal conductivity was also studied within the values (1.17-1.175-1.18) kw/m/k, and these allowable values are taken from the experimental study. This change was inspected during the heating hours, and the comparison was made among the previous three values and the effect of this factor on temperature distribution.

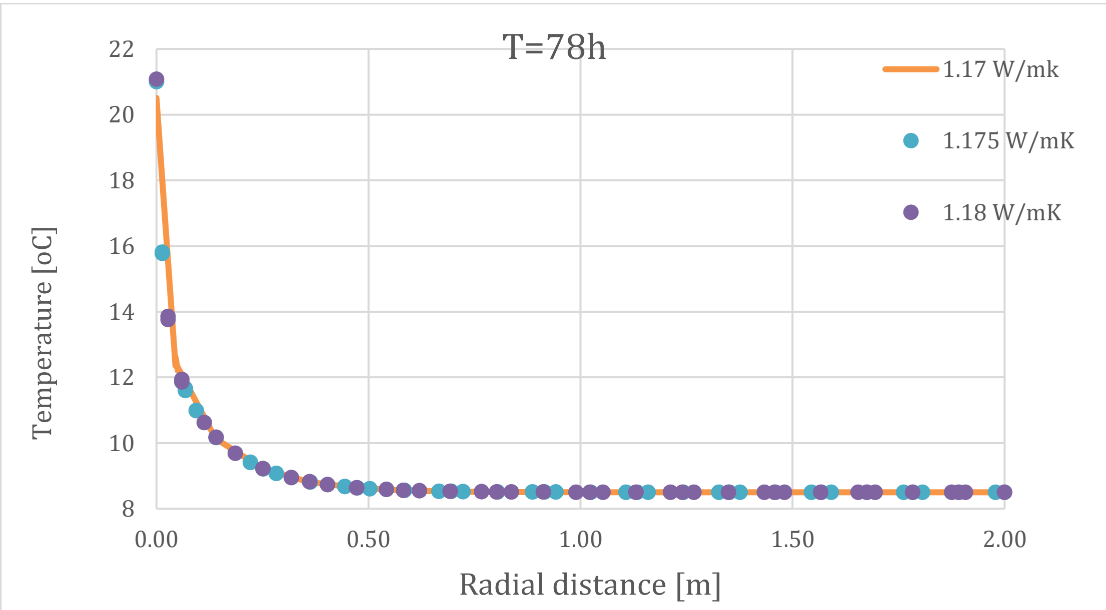


Figure 5-11 expresses the relationship between the temperature and the relative distance from the Pile at h 78 by changing the thermal conductivity values.

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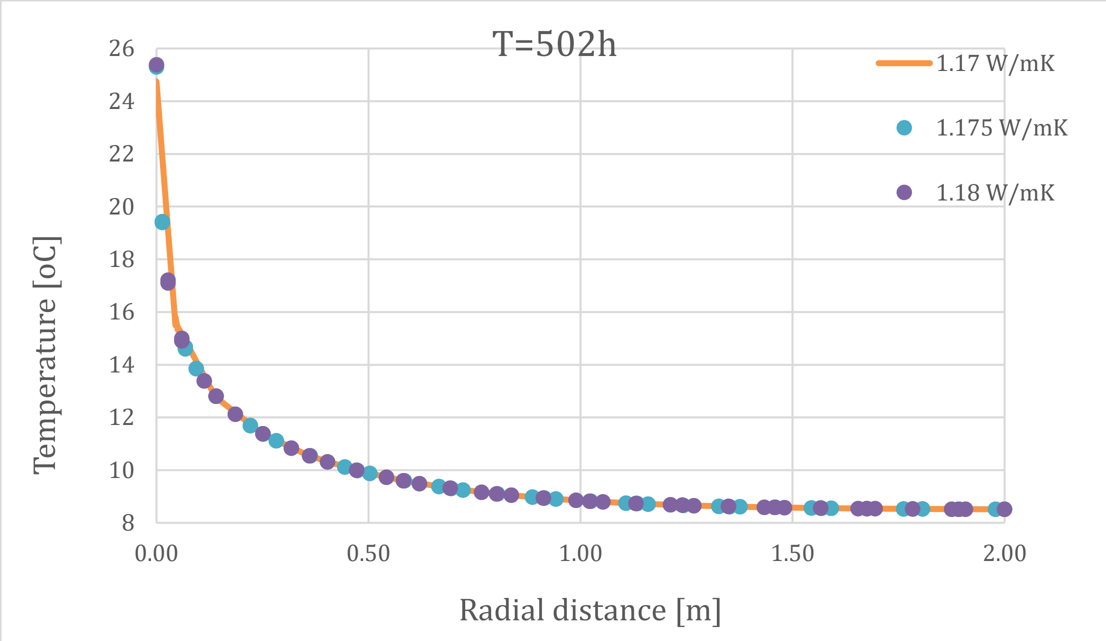

Figure 5-12 Expresses the relationship between the temperature and the relative distance from the Pile at 502 h by changing the thermal conductivity values.

The same comparison was made for two hours during the cooling phase as in the following curves.

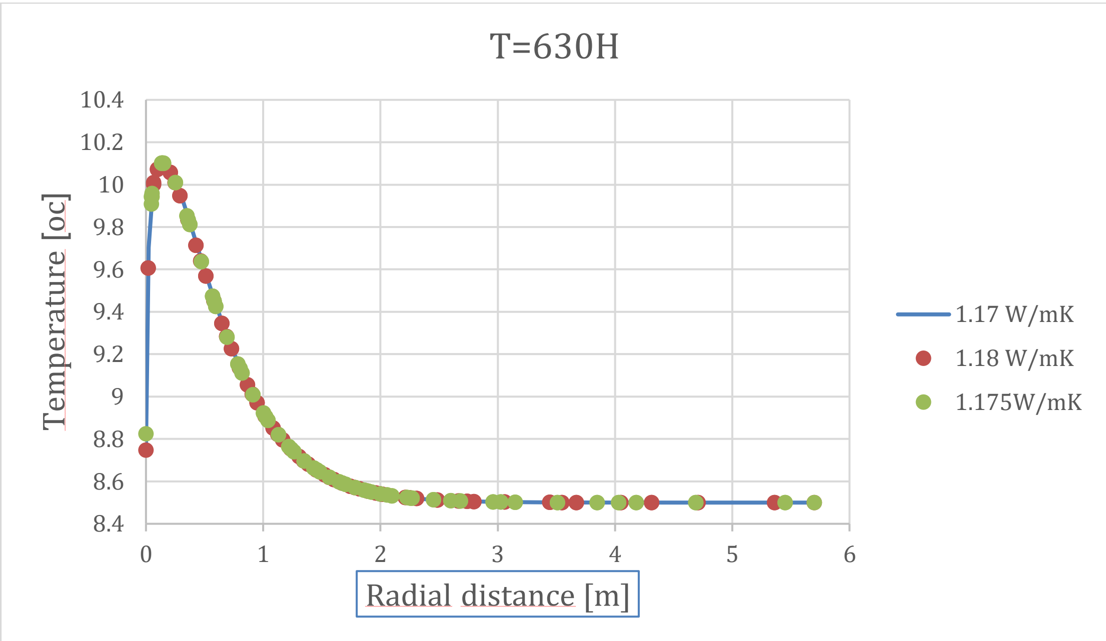

Figure 5-13 expresses the relationship between temperature and the relative distance from the Pile at 630 h by changing the thermal conductivity values.

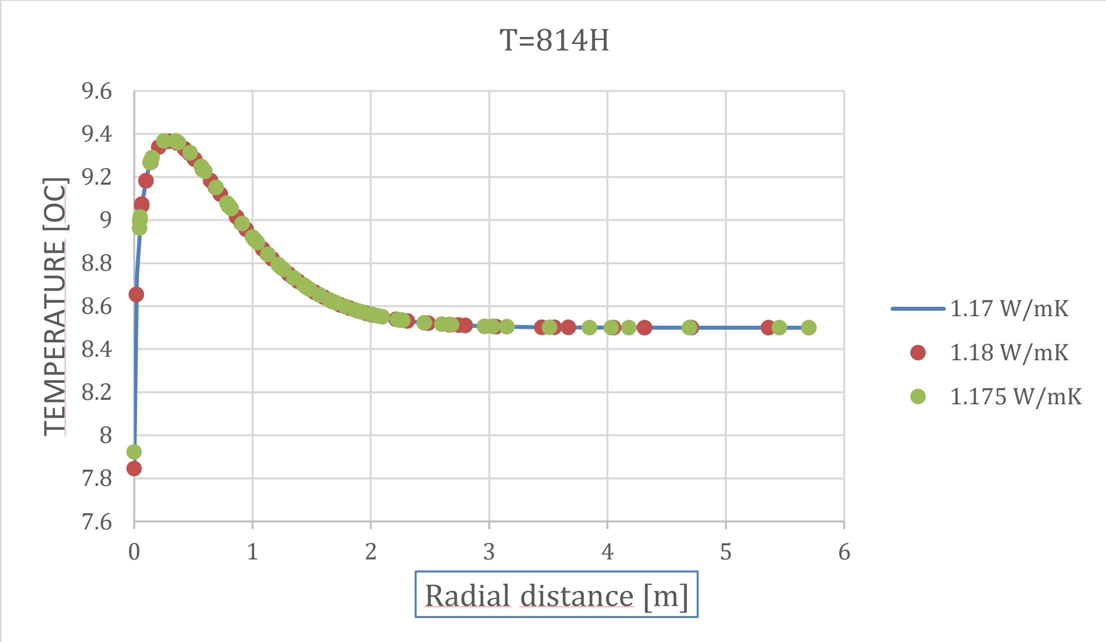

Figure 5-14 Expresses the relationship between the temperature and the relative distance from the Pile at 814 h by changing the thermal conductivity values.

In the second phase of the numerical study, the soil mechanical constitutive model was changed from the Linear Elastic model to the Model Modified Cam Clay model, which considers the plastic response of the soil to compare the results during the heating and cooling stages. The results are as in the following curves.

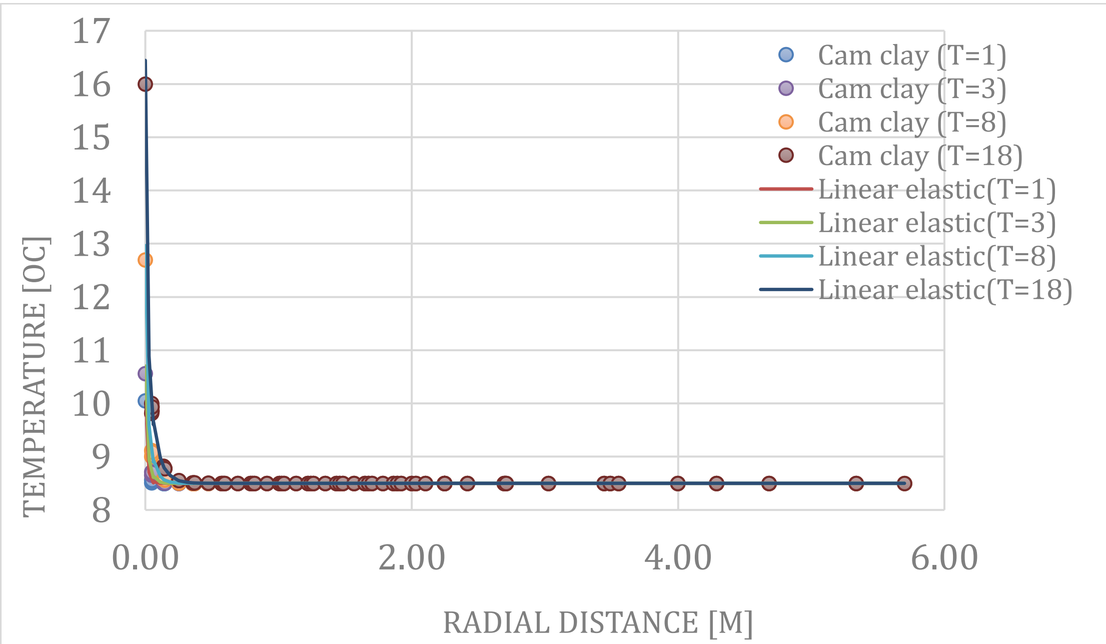

Figure 5-15 Expresses the relationship between temperature and the relative distance from the Pile from 1 h to 18 h by changing the soil model.

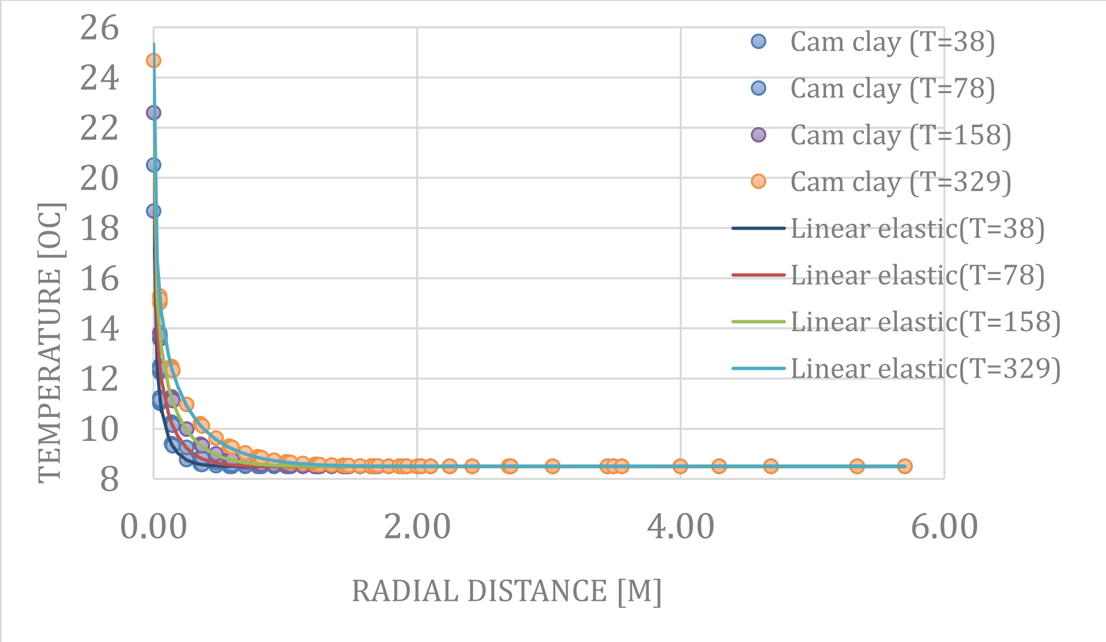

Figure 5-16 Expresses the relationship between the temperature and the relative distance from the Pile from 38 h until 329 h by changing the soil model.

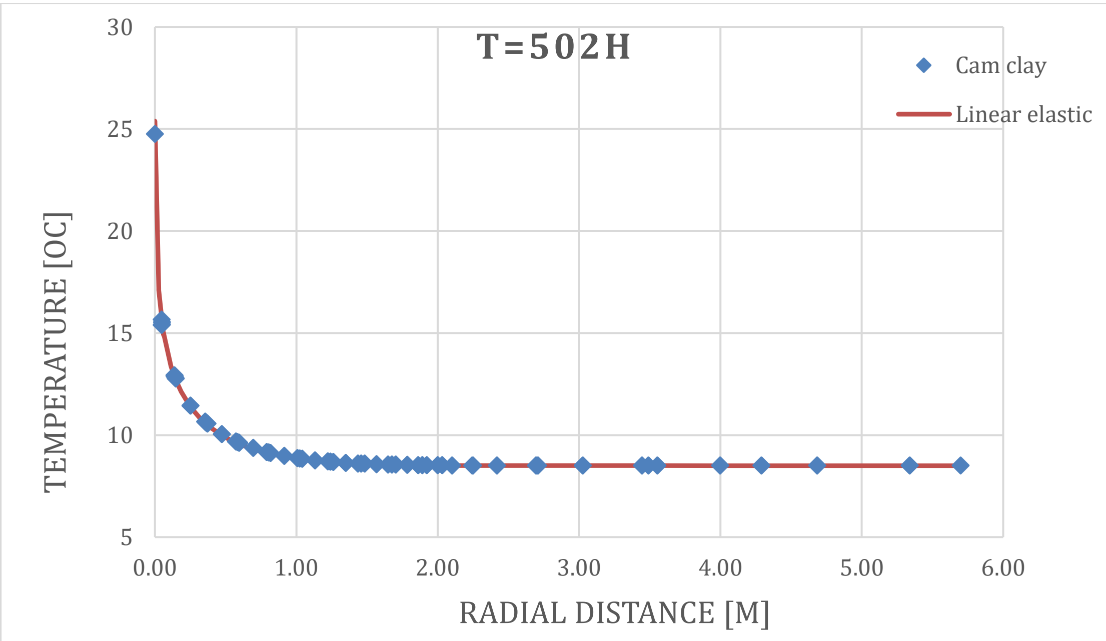

Figure 5-17 Expresses the relationship between the temperature and the relative distance from the Pile at 502 h by changing the soil model.

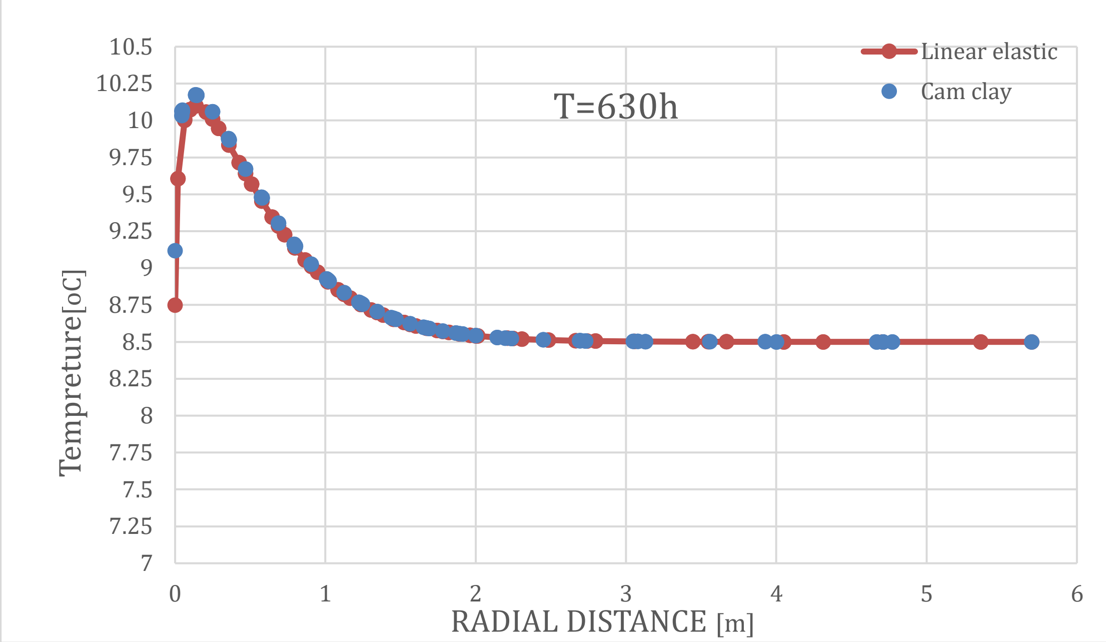

Figure 5-18 Expresses the relationship between the temperature and the relative distance from the Pile at 630 h by changing the soil model.

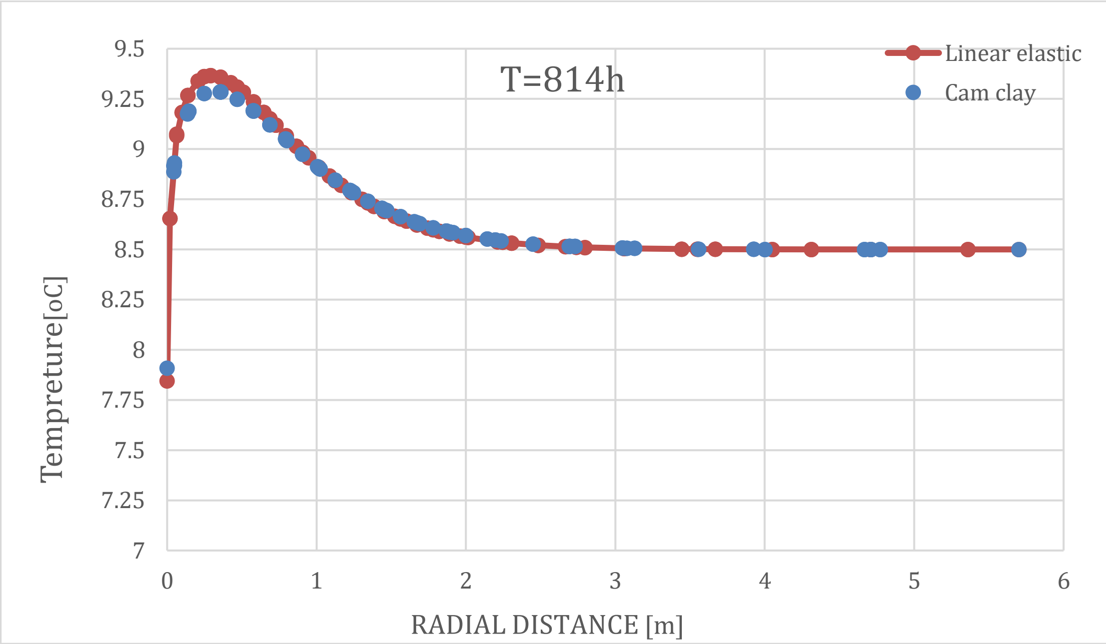

Figure 5-19 Expresses the relationship between the temperature and the relative distance from the Pile at 814 h by changing the soil model.

In the the third stage considers the effect of loading the pile with 90 kN on the temperature changes in the pile and the area around the pile and compared it to loading free pile in the heating and cooling stages during all the hours studied. Curves are drawn that represent the studied hours.

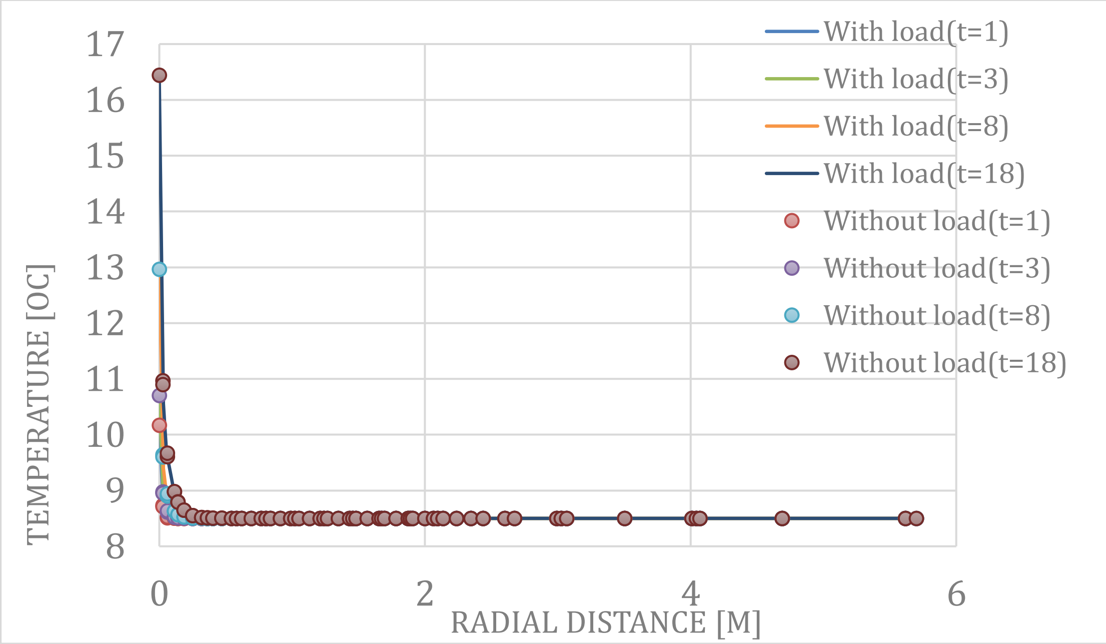

Figure 5-20 Expresses the relationship between the temperature and the relative distance from the Pile from 1 h until 18 h compared to the presence and absence of a load.

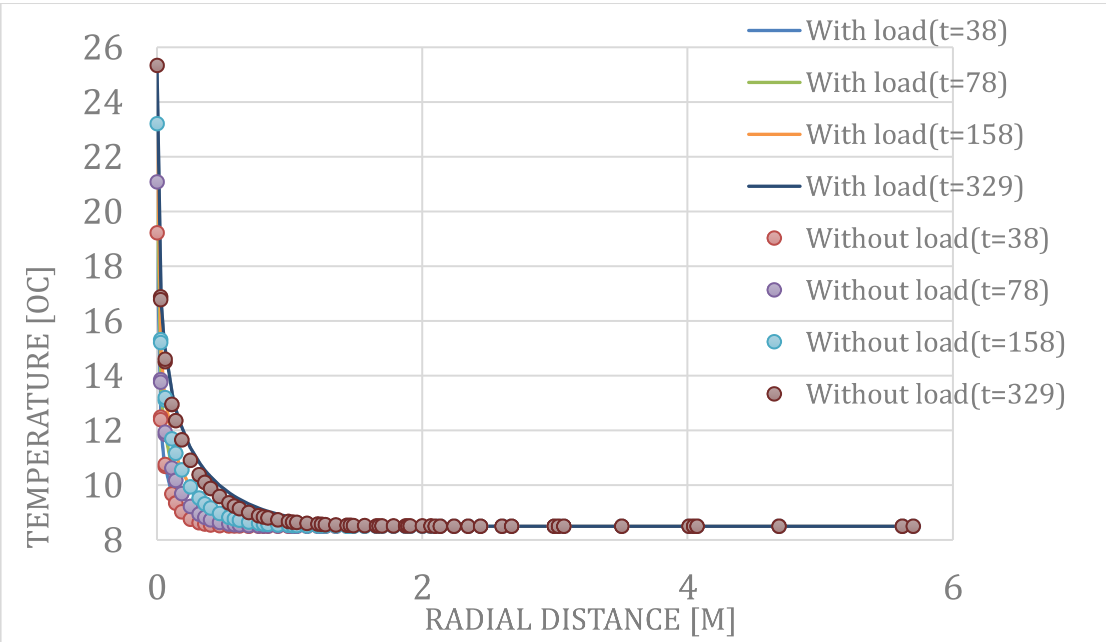

Figure 5-21 Expresses the relationship between the temperature and the relative distance from the Pile from 38 h until 329 h compared to the presence and absence of a load.

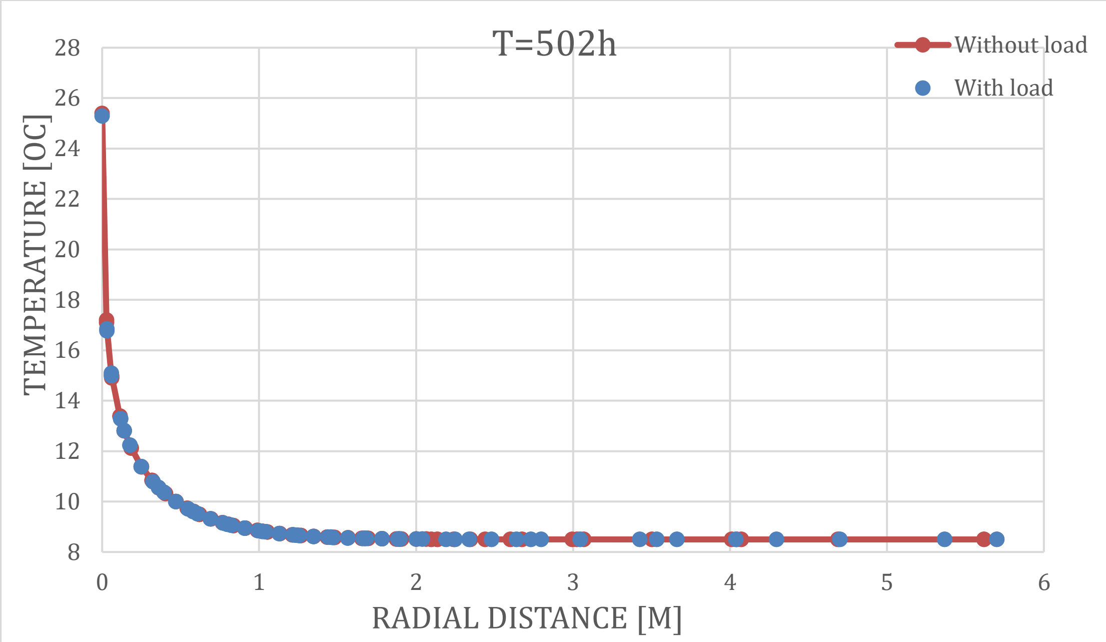

Figure 5-22 Expresses the relationship between the temperature and the relative distance from the Pile at 502 h, comparing the presence and absence of a load.

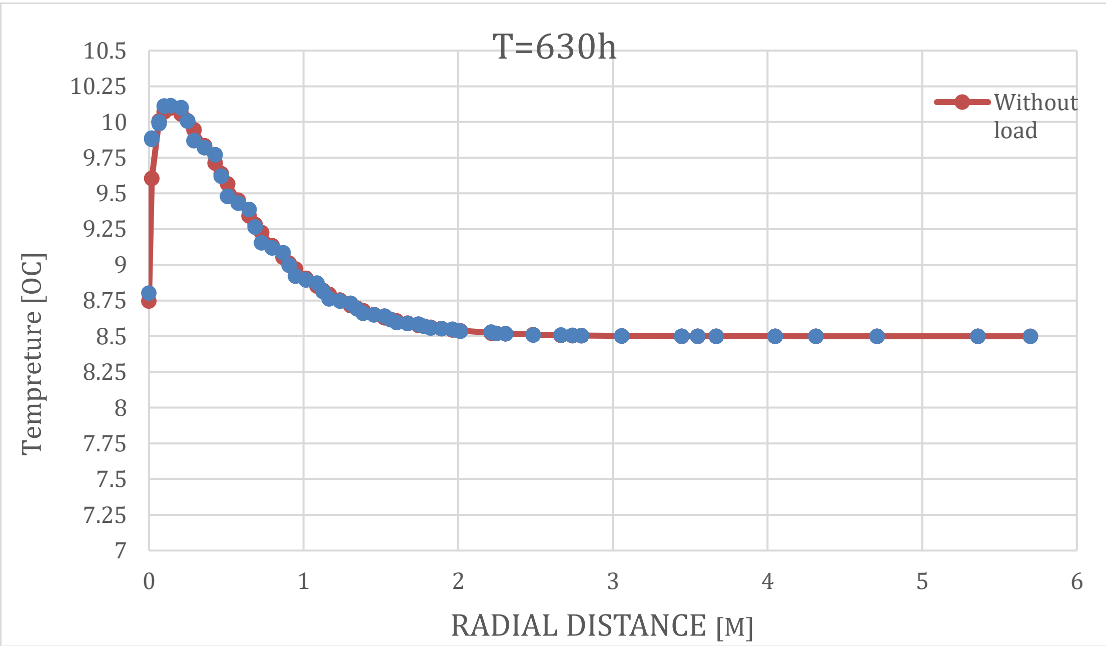

Figure 5-23 Expresses the relationship between the temperature and the relative distance from the Pile at 630 h, compared to the presence and absence of a load.

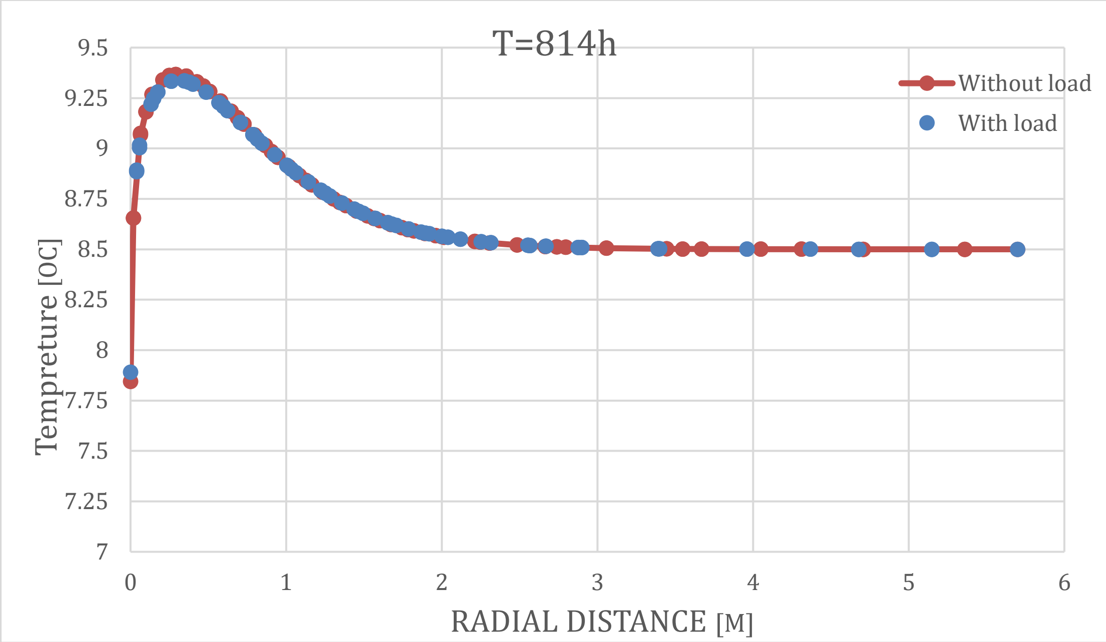

Figure 5-24 expresses the relationship between the temperature and the relative distance from the Pile at 814 h, comparing the presence and absence of a load.

In the last stage, the effect of temperature variation on the excess pore water pressure was studied for different soil mechanical models. The study was initially carried out on the Linear Elastic soil model, and the comparison was made with the experimental results. The following curves display the results.

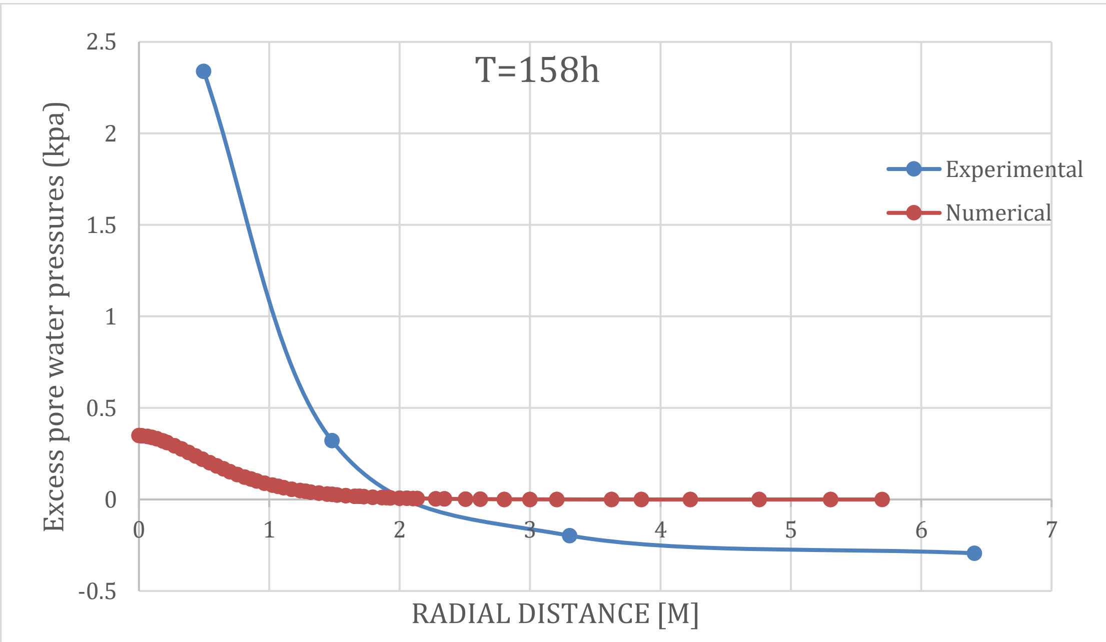

Figure 5-25 Expresses the relationship between excess pore water pressure and the relative distance from the Pile at 158 h using the Linear Elastic soil model.

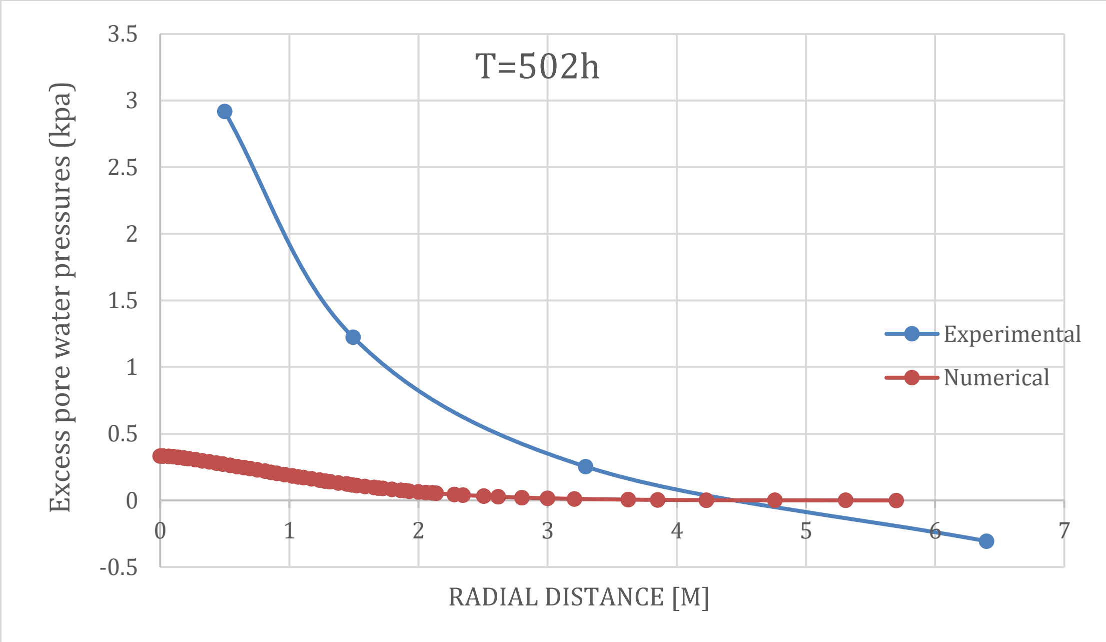

Figure 5-26 Expresses the relationship between excess pore water pressure and the relative distance from the Pile at 502 h using the Linear Elastic soil model.

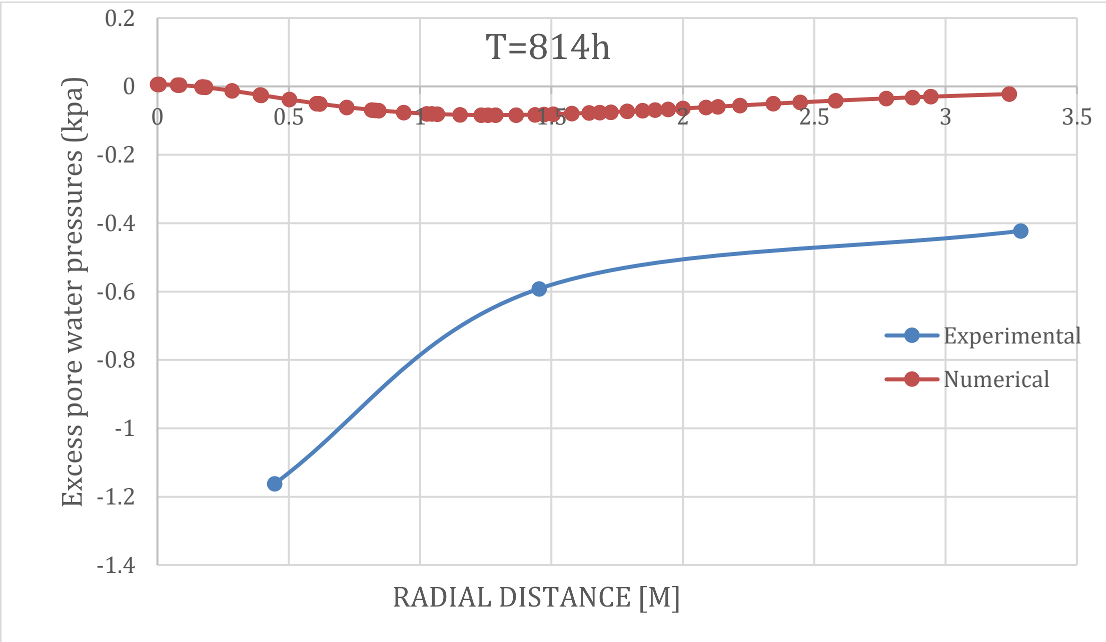

Figure 5-27 Expresses the relationship between pore water pressure and the relative distance from the Pile at 814 h using the Linear Elastic soil model.

The analysis was repeated using the modified cam clay of the soil and compared with the experimental values as in the following curves.

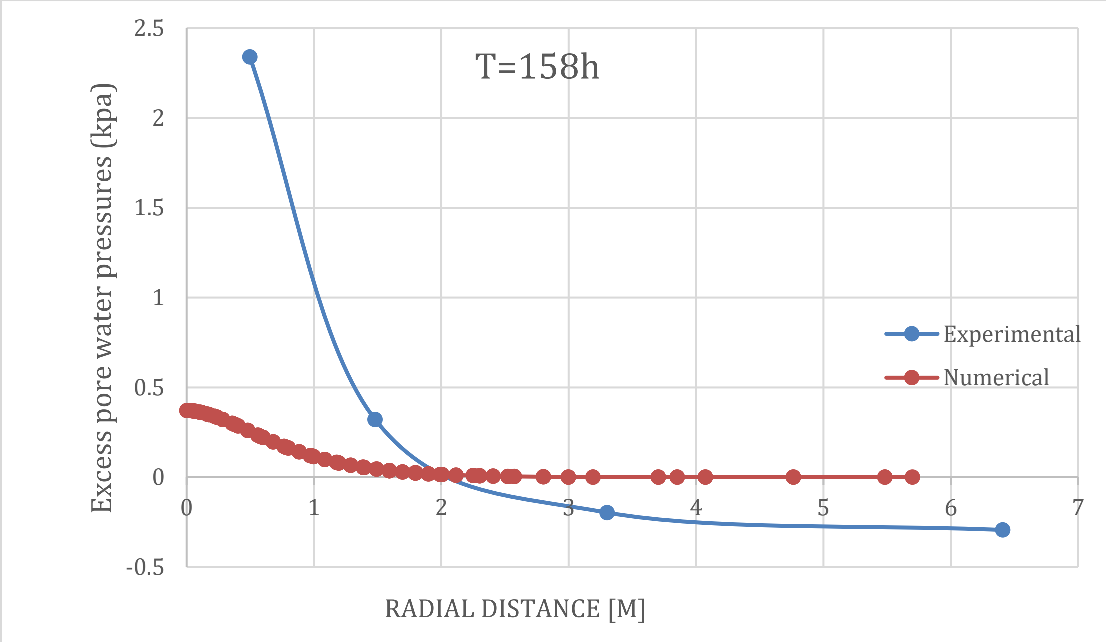

Figure 5-28 Expresses the relationship between pore water pressure and the relative distance *from the Pile at 158 h, using the soil model Modified cam.*

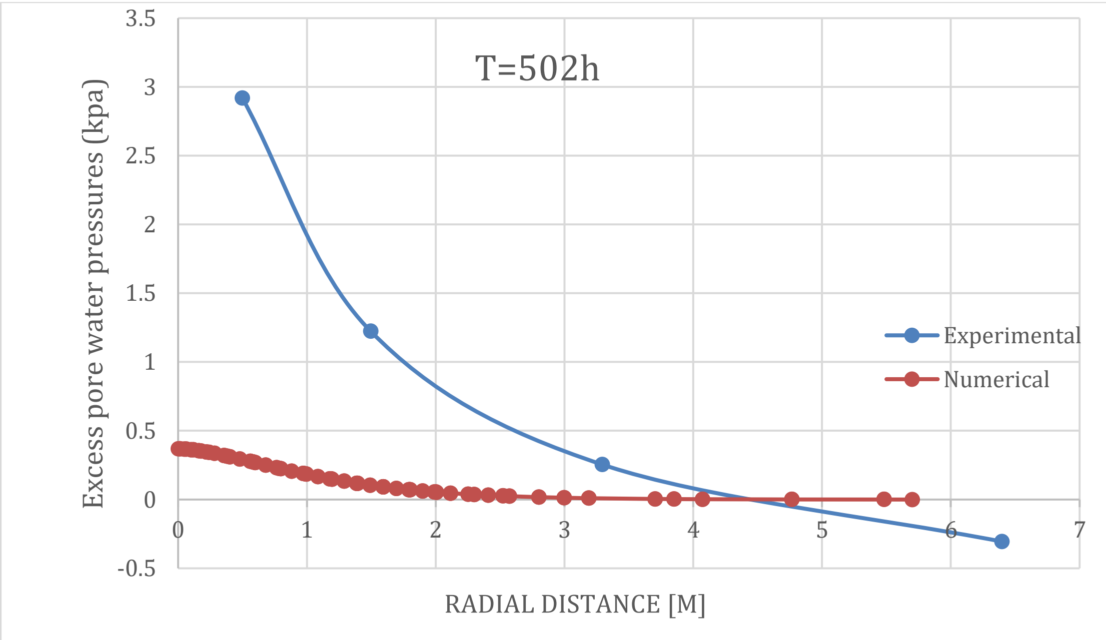

Figure 5-29 Expresses the relationship between ore water pressure and the relative distance from the Pile at 502 h, using the Modified cam-clay soil model.

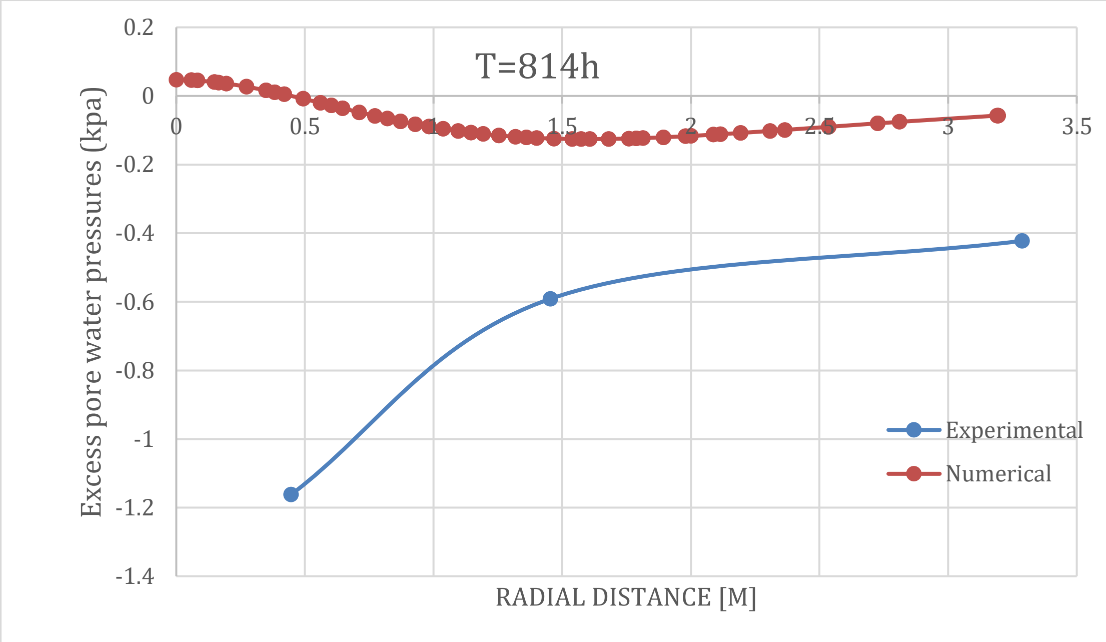

Figure 5-30 Expresses the relationship between pore water pressure and the relative distance from the Pile at 814 h using the Modified cam soil model.

A sensitivity analysis was also carried out to study the influence of changing the thermal expansion coefficient within the allowed values of the soil. Several values are taken for this factor (i.e. 0.01, 0.025, 0.04) and the effect of this change on the value of the excess pore water pressure is recorded. The following charts compare the effect of these three values on the developed excess pore water pressure.

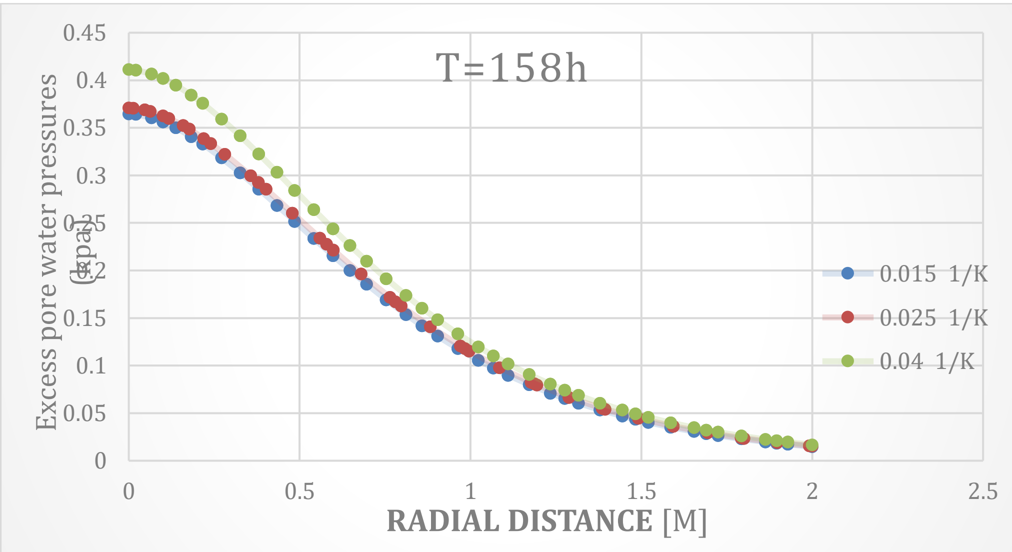

Figure 5-31 expresses the relationship between the pore water pressure and the relative distance from the pile at 158 h by changing the thermal expansion volumetric factor values.

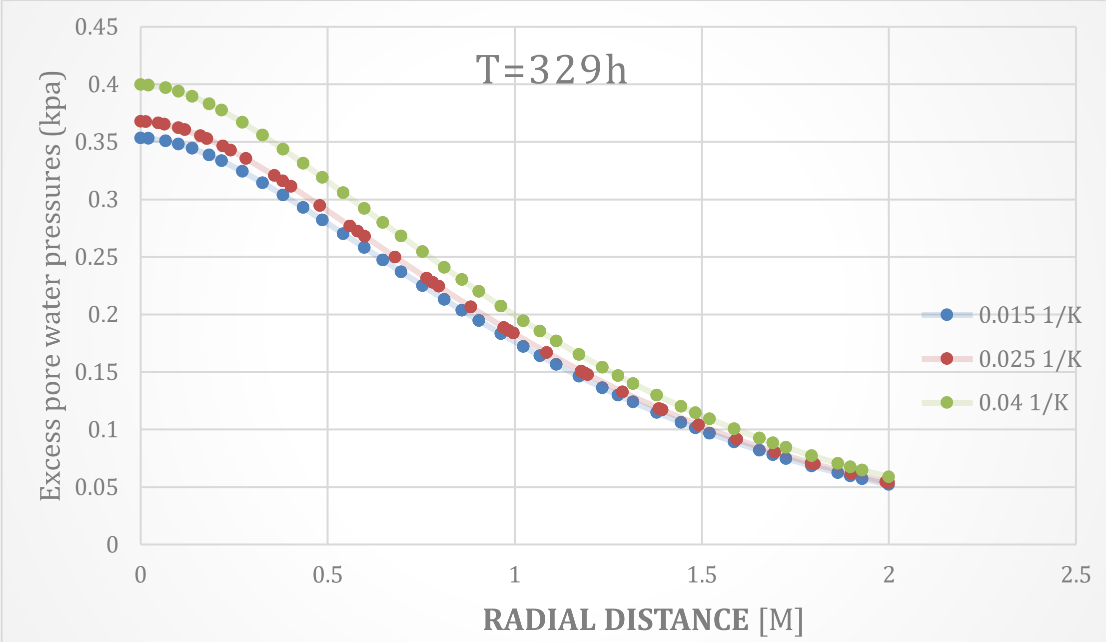

Figure 5-32 Expresses the relationship between the pore water pressure and the relative distance from the Pile at 329 h by changing the values of the thermal expansion volumetric factor.

6 Discussion

1- When heating is applied starting from 1 h to 3 h, that is, during 21 days in the numerical study, it turns out that the numerical analysis is one degree higher than the experimental study in the area near the pile.

2- When heating from 8h until 502h, the experimental study is two degrees higher than the numerical study, converging after 1m from the pile.

3- During the cooling process, it was found that the numerical study is one and a half degrees higher than the experimental study near the Pile. Then, the temperature rises at 0.5 m from the Pile and then returns to the initial temperature of the ground at 8.5 at a distance of 2 m from the pile.

4- When studying the thermal conductivity coefficient and its effect on the cooling and heating process, it was found that its impact on the temperature distribution and the differences are not apparent; therefore, the changes in this factor did not affect the thermal flow.

5- The results coincide when studying the heat capacity factor within the permissible values and its effect on the cooling and heating process, indicating a negligible impact of this factor within the factor range in the heating and cooling process.

6- When changing the soil model from Linear Elastic to the critical state Cam Clay model, it was found that the elastic model gave results that is half a degree more than the Modified Cam Clay during the early hours of the test (i.e. from 1h until 8h) and one degree more from 38h until 502h near the Pile. In the cooling phase, both models yielded identical results.

7- Applying a point static load of 90kN on the Pile has no significant effect on the temperature and excess pore water pressure during heating and cooling phases.

8- The excess pore water pressure was studied using the Linear Elastic and the Modified Cam Clay and compared with the experimental study. The test indicated that the excess pore water pressure was higher during heating phase and varied between 0-3 kPa starting from the area near the Pile until after 3m from it. The numerical results barely showed any excess pore water pressure due to temperature and ranged from 0.4 near the Pile to become 0 on the 3m away from it. In the cooling phase, the experimental results showed suction values from -1.2 to -0.4, while the numerical value fluctuated between 0.2 near the Pile and returned to values close to zero at 3m from the Pile.

9- The effect of the thermal expansion coefficient on the excess pore water pressure was studied. It was found that the excess pore water pressure increased with the increase of the thermal expansion coefficient but not enough to capture the measured data.

7 Conclusion

The results indicate a good match between the numerical and experimental study in terms of temperature distribution during heating and cooling phase, and therefore, the numerical framework works reasonably well when simulating the heat flow.

The numerical study indicates that with the current implementation of Plaxis2D, the models of different mechanical materials models do not capture well the thermal effect in terms of excess pore water changes, at least for the studied type of sensitive Gothenburg clay.

The sensitivity analysis shows that changes in thermal properties, including the thermal conductivity, the heat capacity and the thermal expansion coefficient, have limited effect on the results.

8 Recommendations

- It is recommended to develop a more advanced material model that is sensitive to the thermal effects and able to replicate better the evolution of the excess pore water pressure.

- The current study only focused on the so-called thermal response test. It would be recommended to model also cyclic thermal loading part of the test and check on the ability of the numerical code to capture the measured responses.

- Studying the behaviour of a group of Piles with or without a hat and the effect of the presence of several Piles on the distribution of heat in the soil would be interesting from practical point of view.

- Studying the behaviour of other types of thermal Piles (e.g. concrete) and its effect on the surrounding soil would be recommended to compare its performance to the steel.

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10 APPENDIX

10.1 Supplementary results to the numerical study in Plaxis2D as provided in the main text of the thesis:

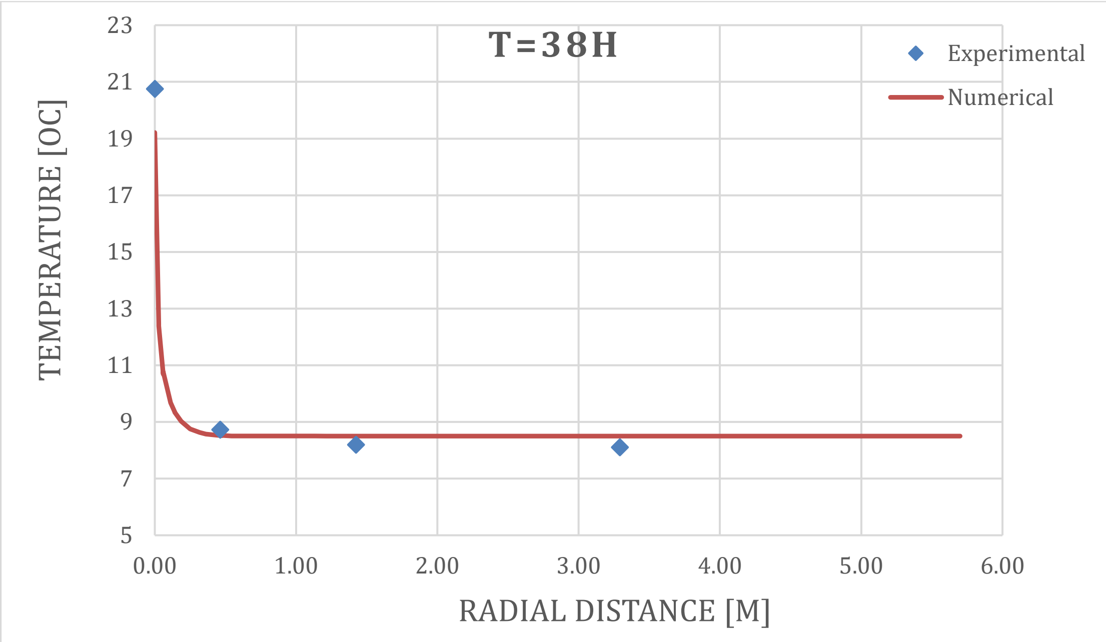

Figure 0-1 expresses the relationship between temperature and the relative distance from the pile starting at 38h

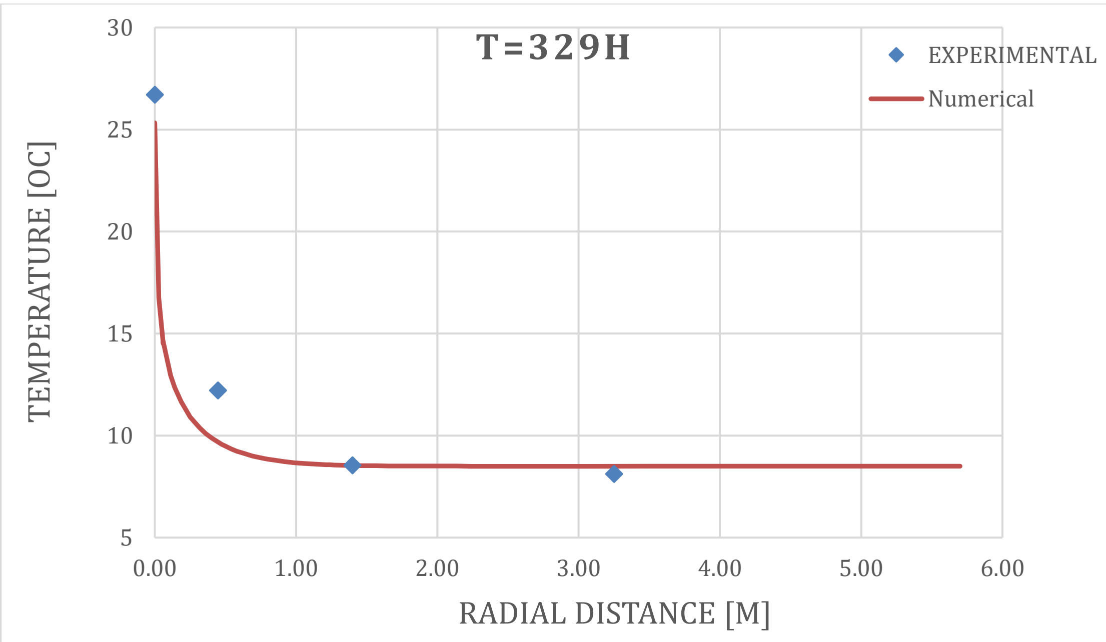

Figure 0-2 Expresses the relationship between temperature and the relative distance from the pile starting at 329h.

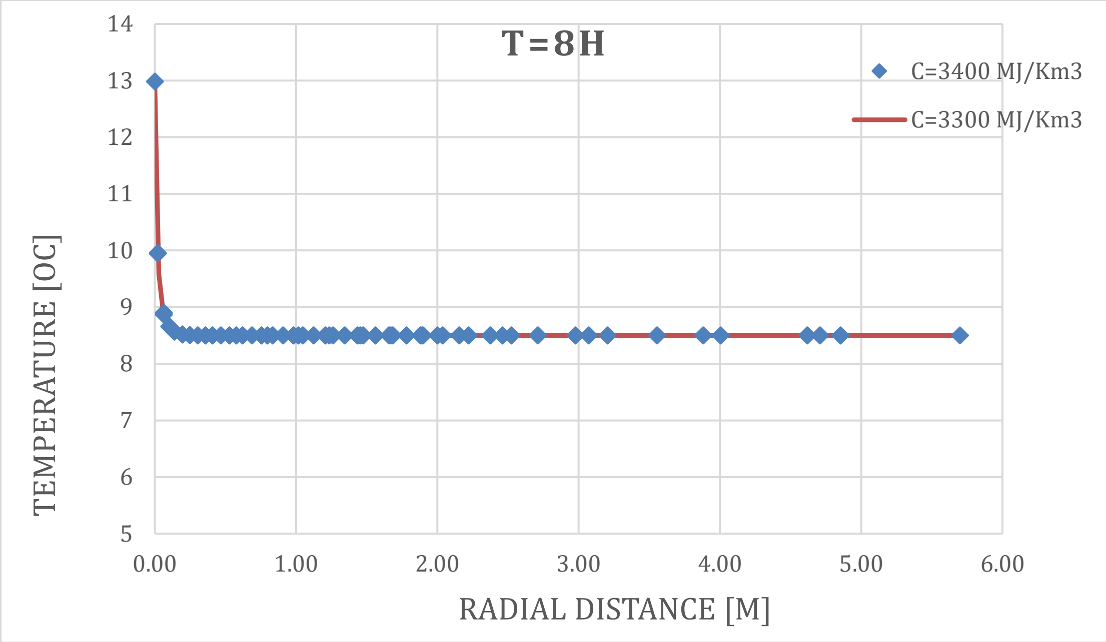

Figure 0-3 expresses the relationship between the temperature and the relative distance from the Pile starting at 8h changing the heat capacity values

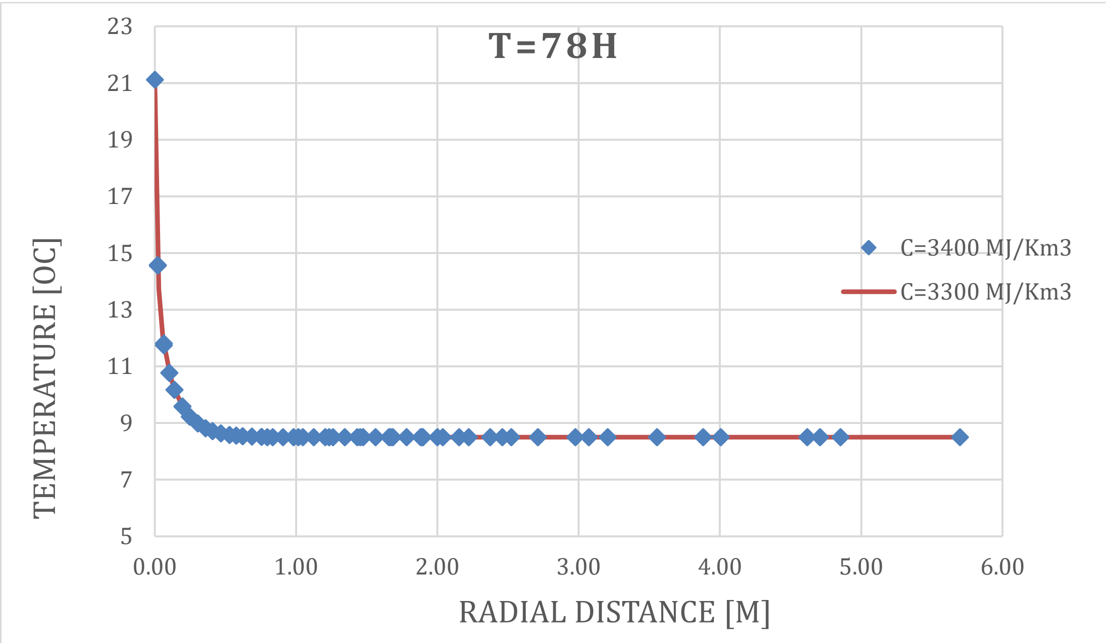

Figure 0-4 expresses the relationship between the temperature and the relative distance from the Pile starting at 78h changing the heat capacity values

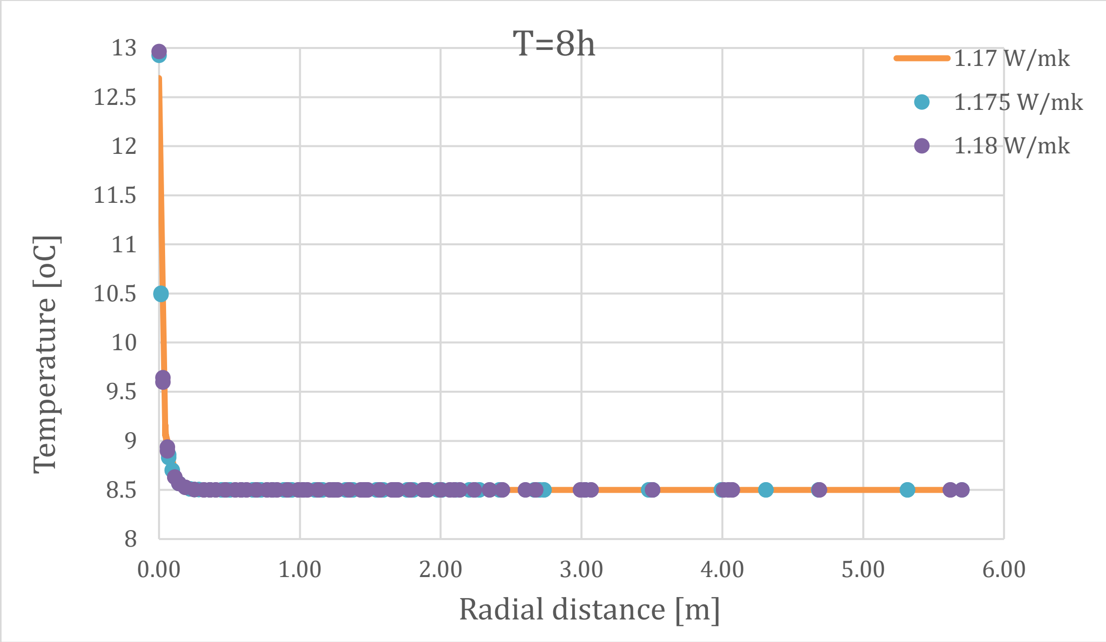

Figure 0-5 Expresses the relationship between the temperature and the relative distance from the Pile at 8h by changing the thermal conductivity values

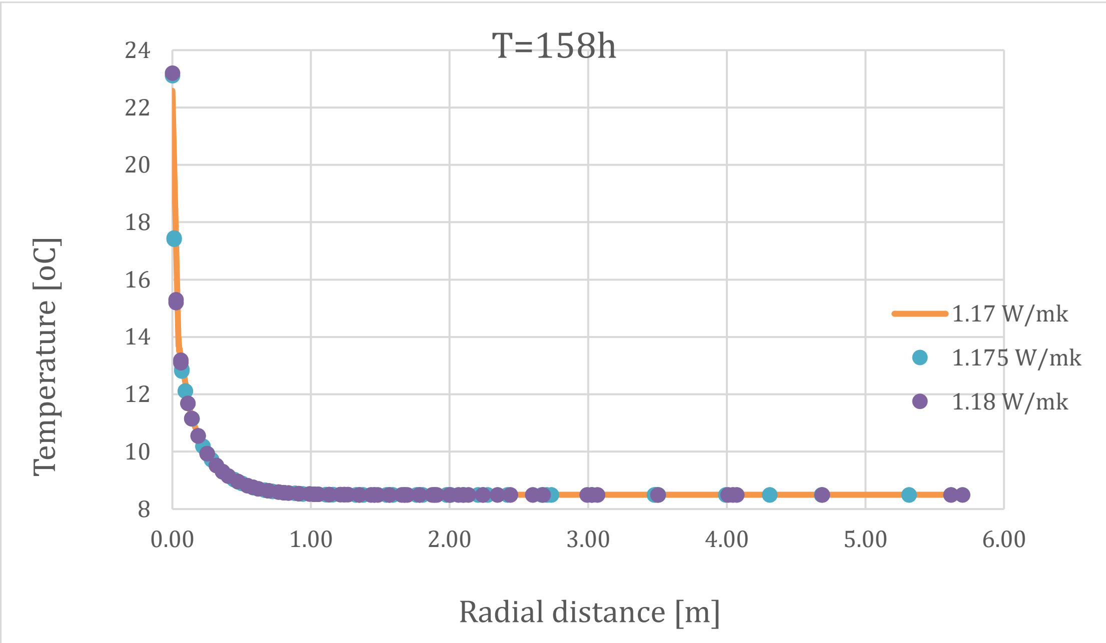

Figure 0-6 Expresses the relationship between the temperature and the relative distance from the Pile at 158h by changing the thermal conductivity values

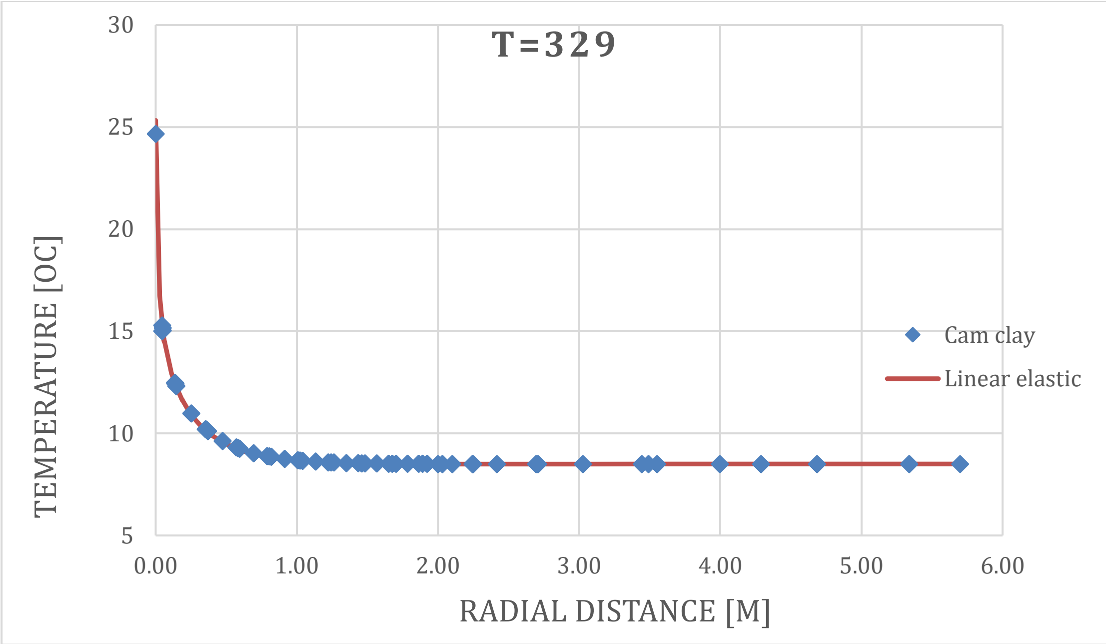

Figure 0-7 Expresses the relationship between the temperature and the relative distance from the Pile at 329h by changing the soil model.

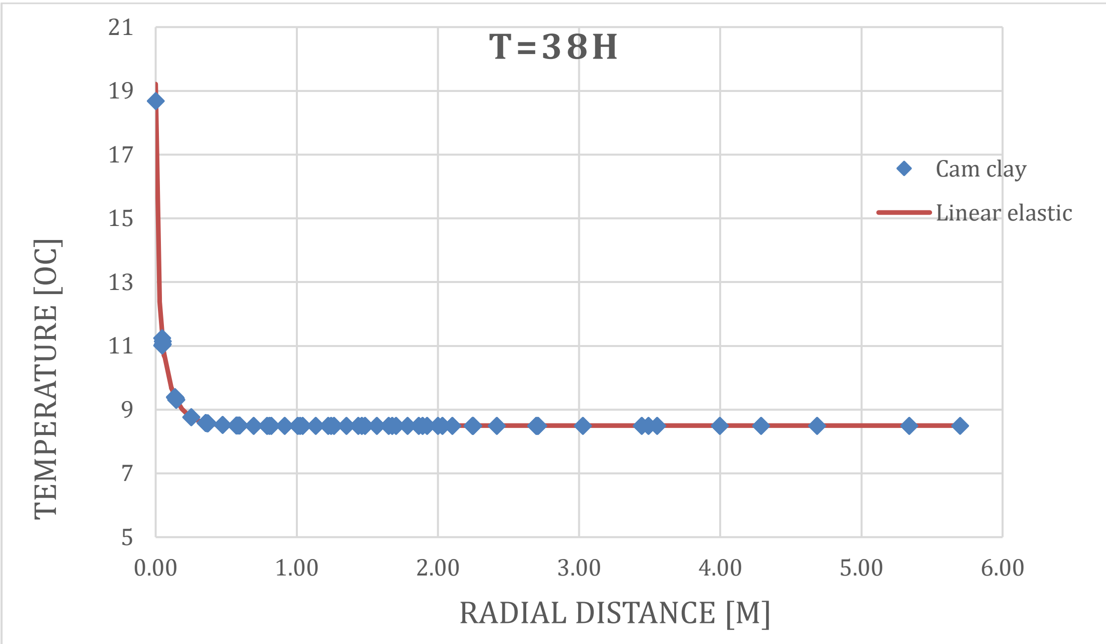

Figure 0-8 Expresses the relationship between the temperature and the relative distance from the Pile at 38h by changing the soil model.

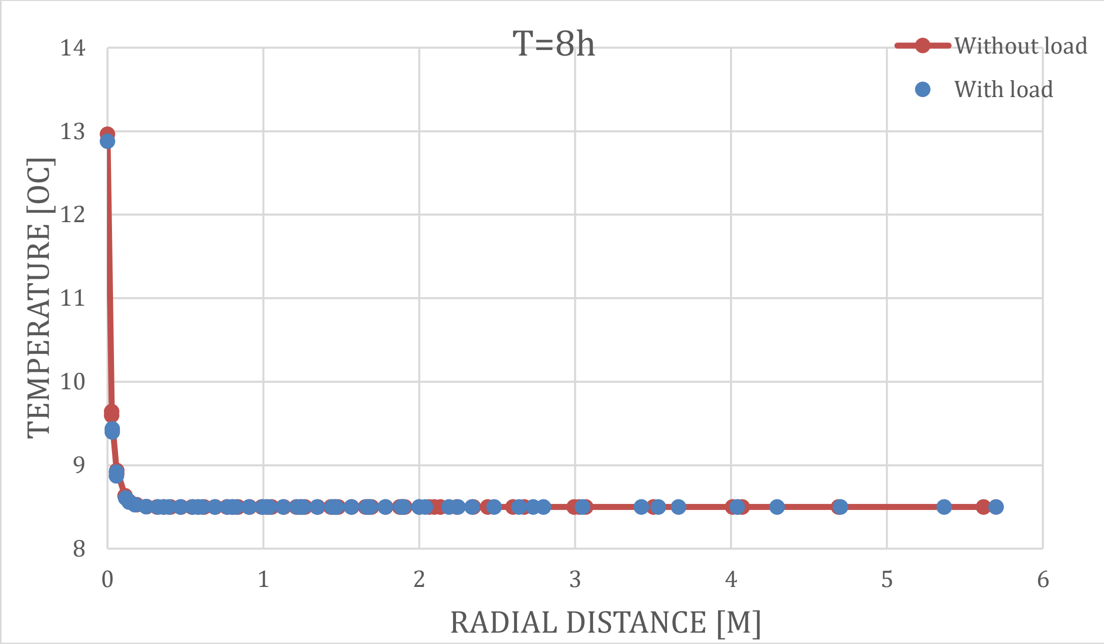

Figure 0-9 Expresses the relationship between the temperature and the relative distance from the Pile at 8 h, comparing the presence and absence of a load.

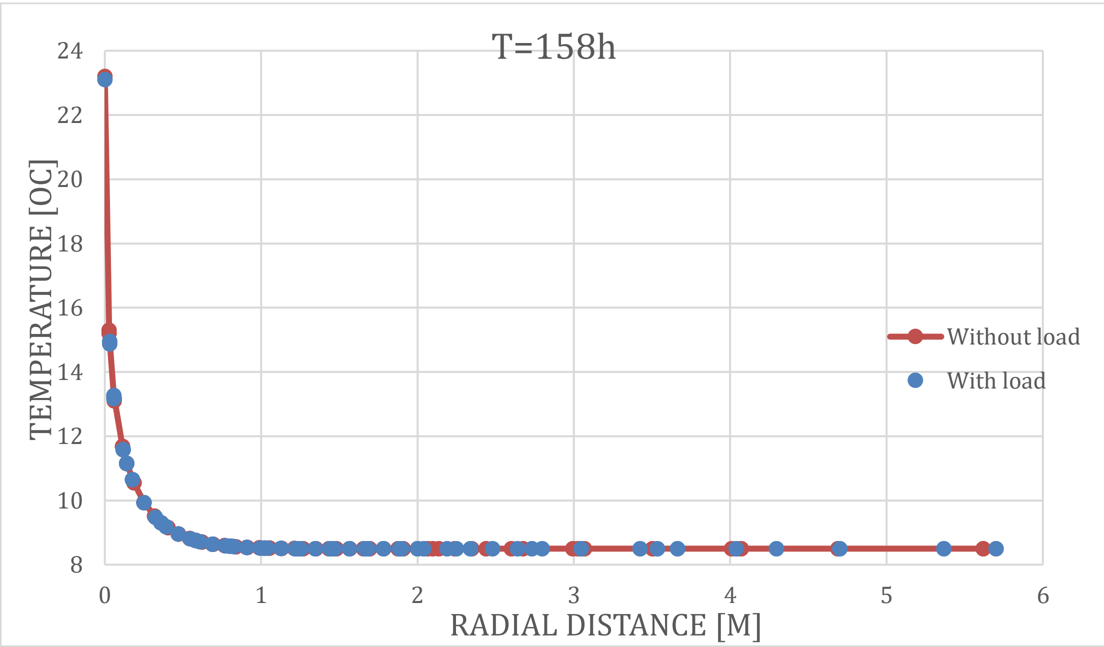

Figure 0-10 Expresses the relationship between the temperature and the relative distance from the Pile at 158 h, comparing the presence and absence of a load

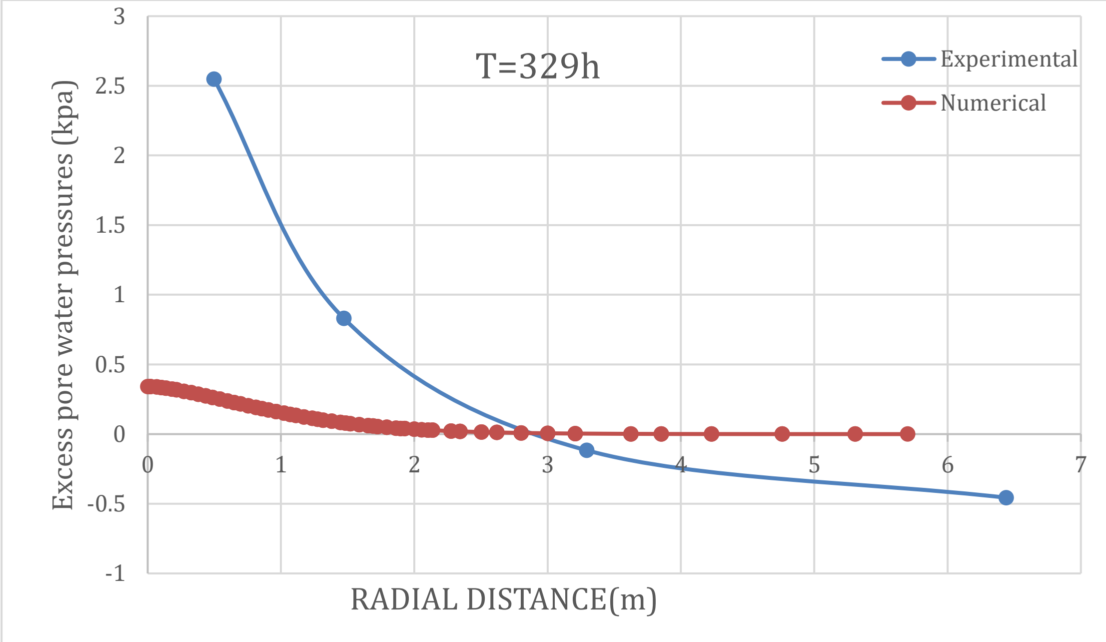

Figure 0-11 Expresses the relationship between pore water pressure and the relative distance from the Pile at 329 h using the Linear Elastic soil model.